W7-X Physics Meeting
20 January 2025

EUROfusion

Intro to ICRH at W7-X and consequences for operations

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Basic properties

Ion Cyclotron frequency f

$$\omega = 2\pi f = \frac{q_e B}{m_p} \frac{Z}{A}$$

(15.25 MHz per Tesla for H)

Resonance location for given frequency (for tokamak R dependence of B-field)

$$R|_{\omega=N\omega_{ci}} \approx R_0 \times N \times (Z/A)_{\mathrm{i}} \times \frac{15.25 B_0(\mathrm{T})}{f(\mathrm{MHz})}$$

- Frequency of launched waves by ICRH antenna
- For fixed antenna frequency and B field, resonance location determined by Z/A of the respective ion.

ICRH Is a flexible method:

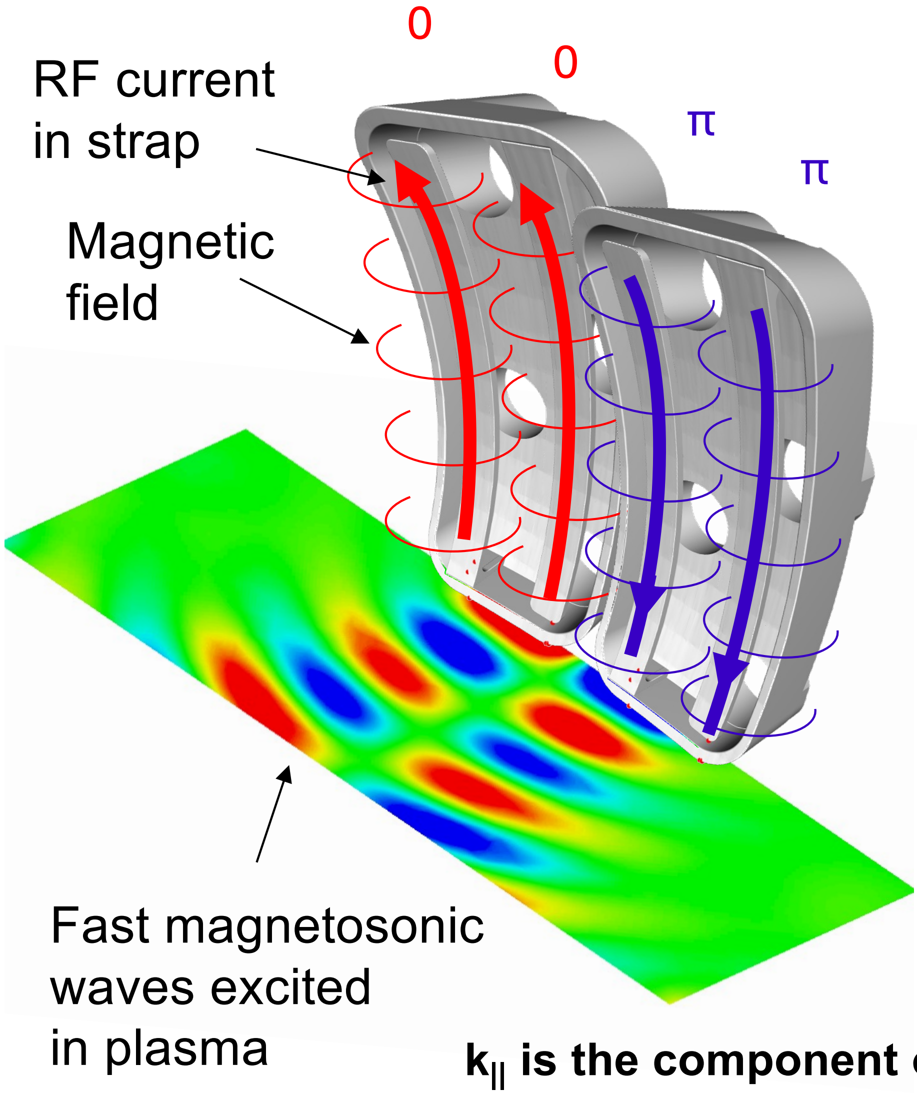
- heat ions with given Z/A as ω ~ (Z/A)

- heat ions at specific location as ω ~ (B_0/R)

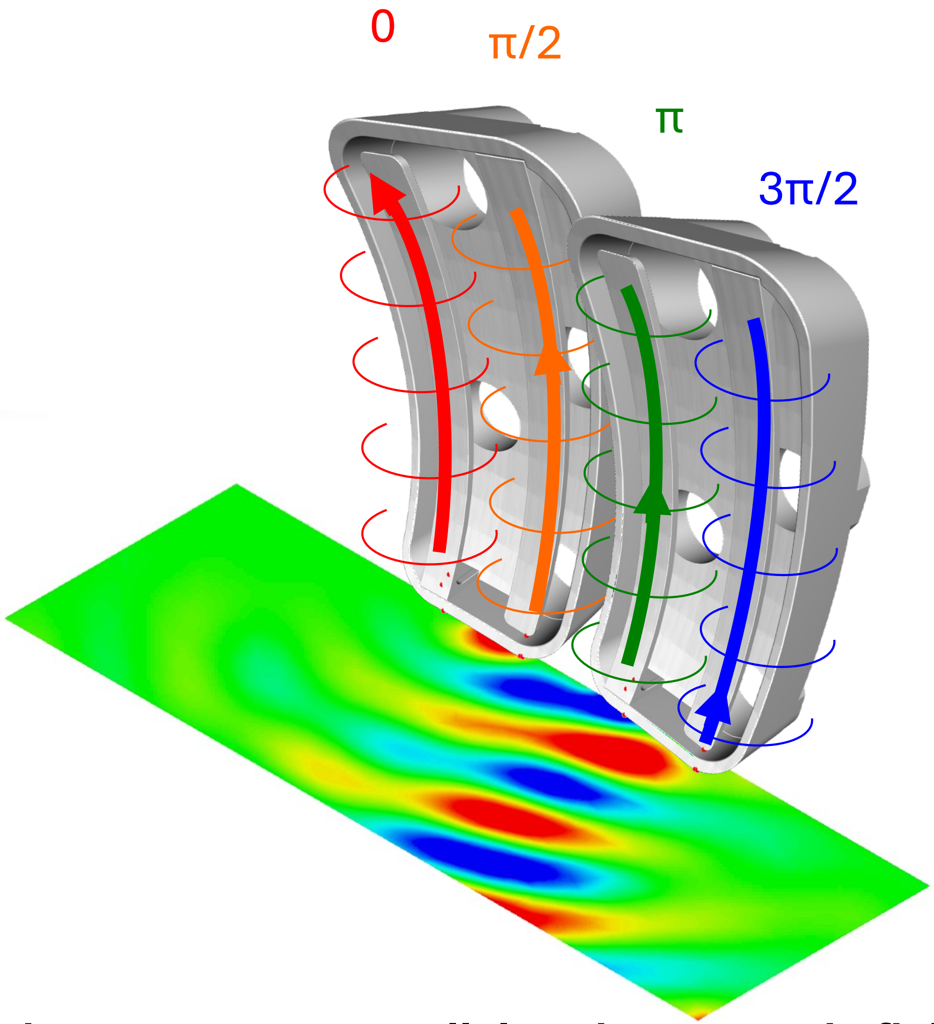
Phasing of antenna straps and $k_{||}$ value

Strap current phasing determines dominant $k_{//}$ and wave directivity

Symmetric wave propagation



Asymmetric wave propagation

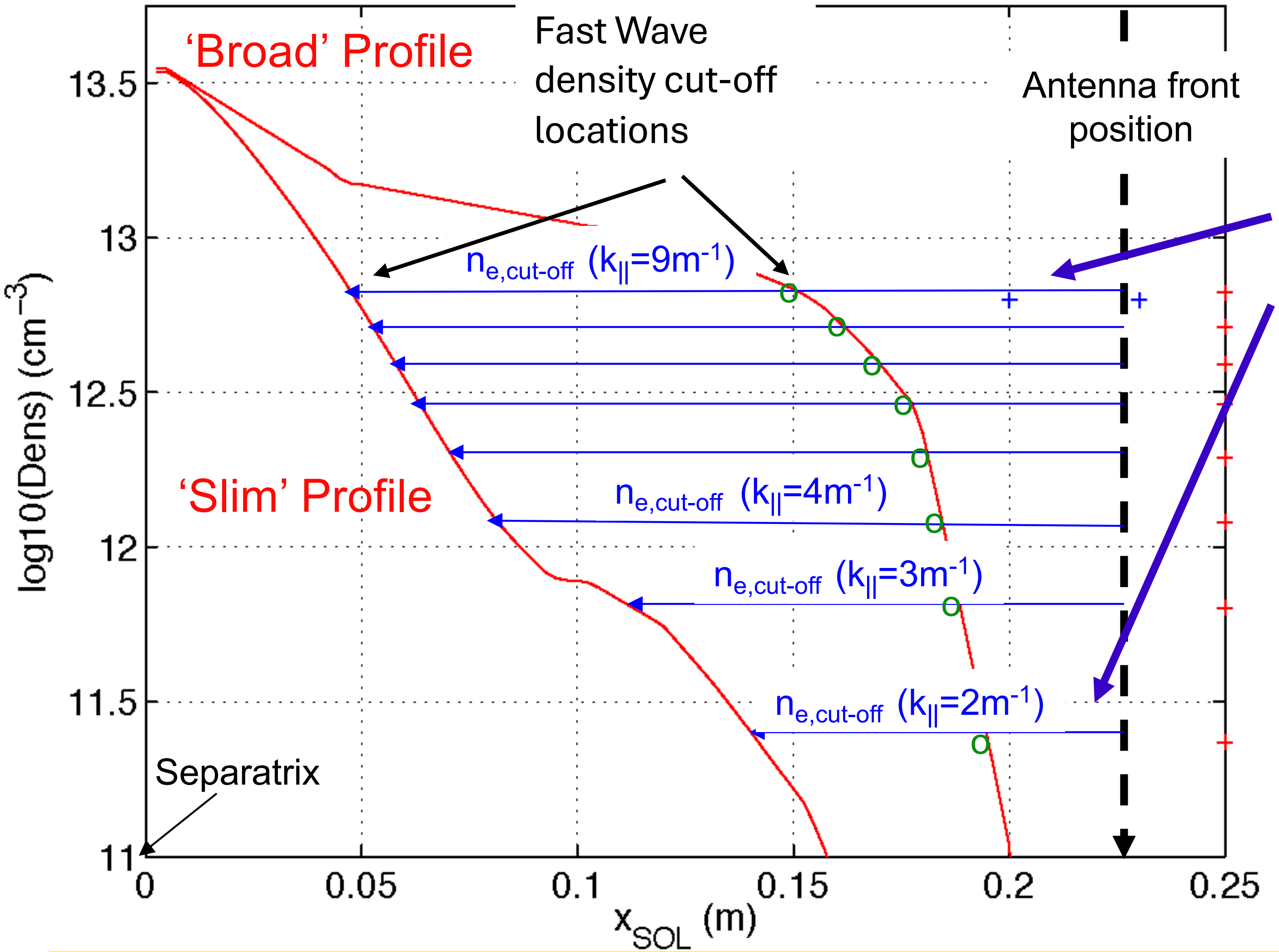


$k_{||}$ is the component of the wavevector parallel to the magnetic field

$k_{||}$ determines waves propagation and absorption

Coupling depends on edge density profile and $k_{||}$ value

Illustrated by 2 density profiles



Wave Propagation through evanescence layer

$\propto \exp(-\alpha\, |k_{||}|\, L_{evan})$

$\alpha \sim 1$

L_{evan} evanescence length from antenna up to $n_{e,cut-off}$

- ➛ 'slim' profile: larger L_{evan}
- ➛ coupling less optimal

Absorption at plasma $\propto k_{||}$

Cut off density $\propto k_{||}^2$

Gas puffing in front of antenna helps to improve RF coupling

ICRH system in W7-X

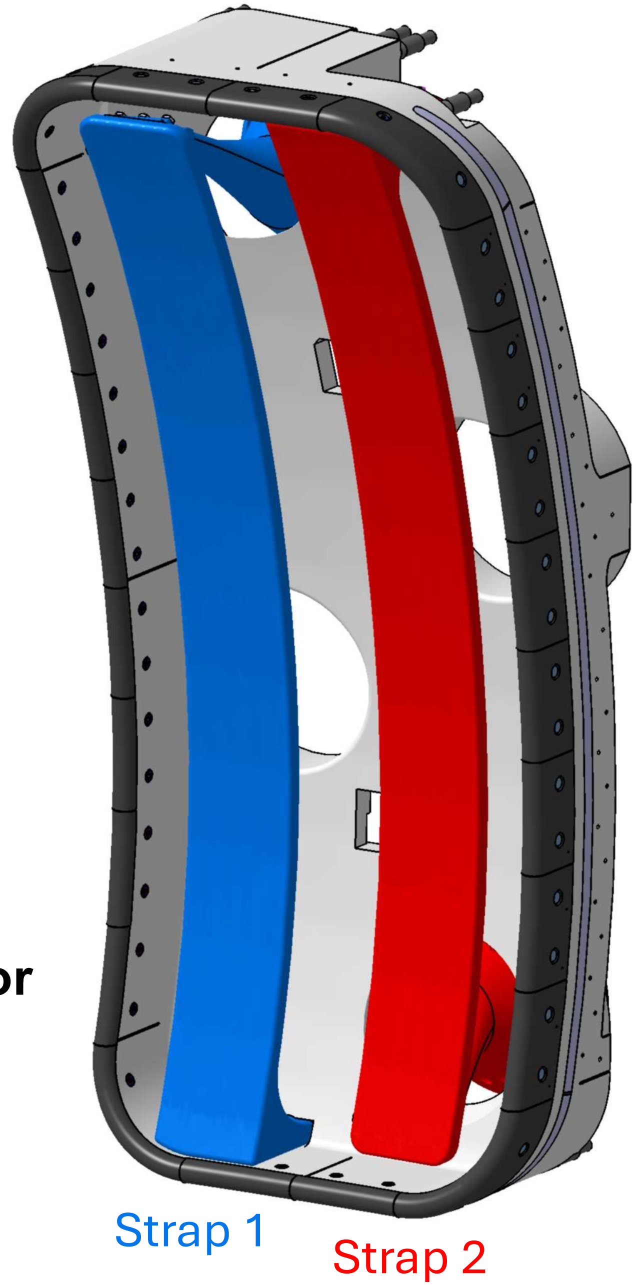
- **A two-strap antenna without Faraday Screen**
  → **3-D shaped** ***(aligned with the LCMS for the standard configuration)***

  → **flexible RF current phasing between the straps** ***($k_{||}$-spectrum and coupling)***

- **Frequency range *f* = 25-38 MHz**

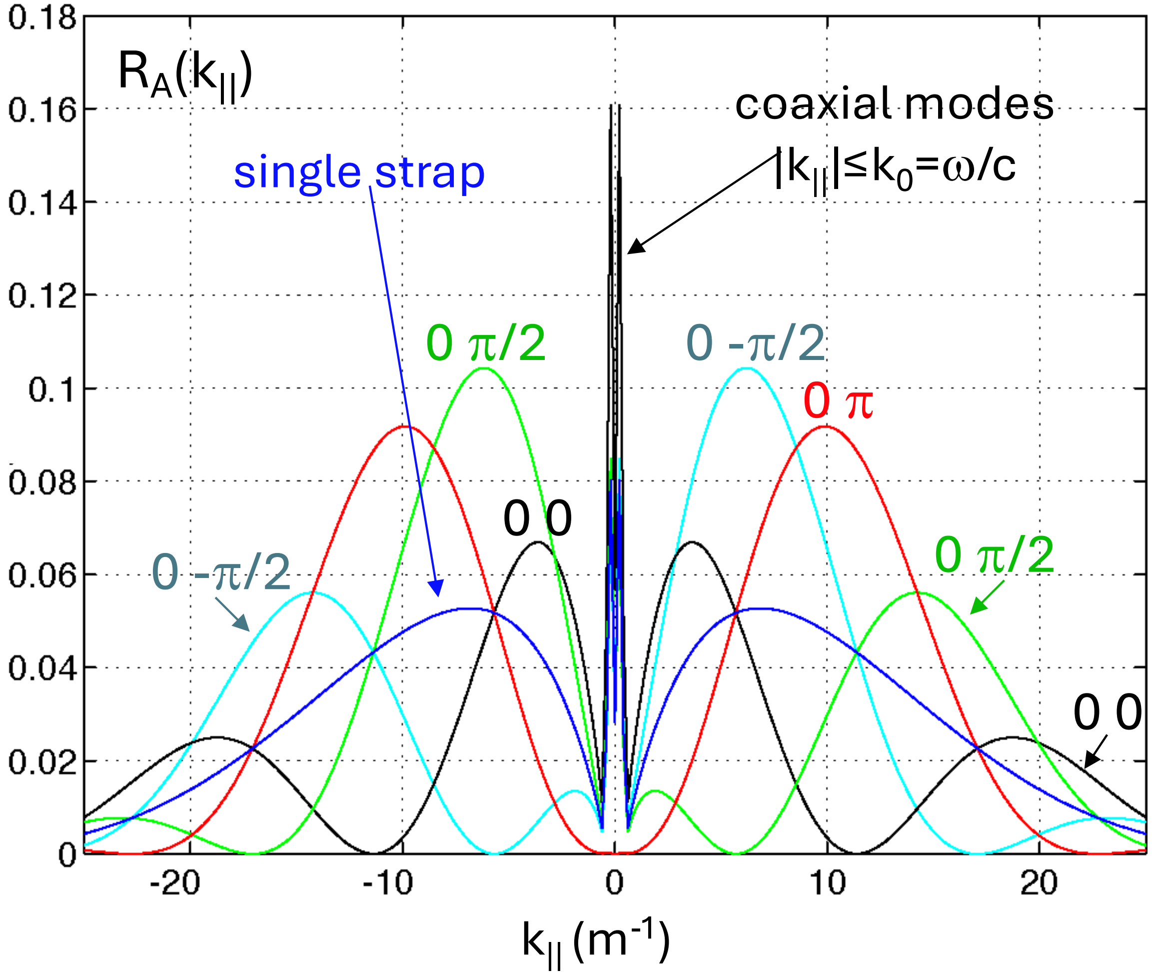
- **Pulsed mode operation: up to 10s (every 3 minutes)**

- **Main Aim: fundamental test of the confinement of fast particles in view of a future Helias fusion reactor**



J.Ongena et al., Phys. Plasmas 21, 061514 (2014)
B.Schweer et al., Fus. Eng. Design 123, Pages 303-308 (2017)
D.A. Castaño Bardawil et al., Fus. Eng. Design. 166 112205 (2021)

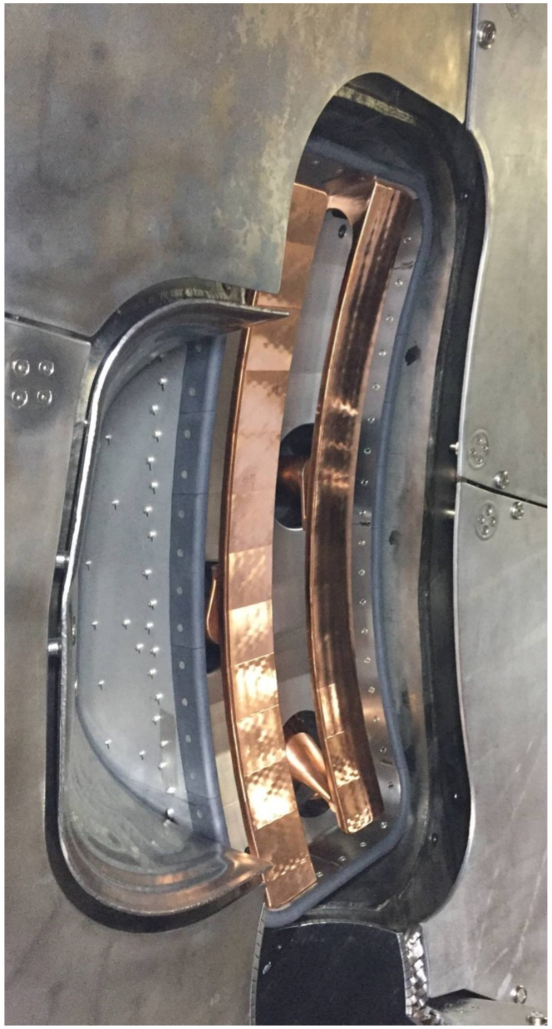
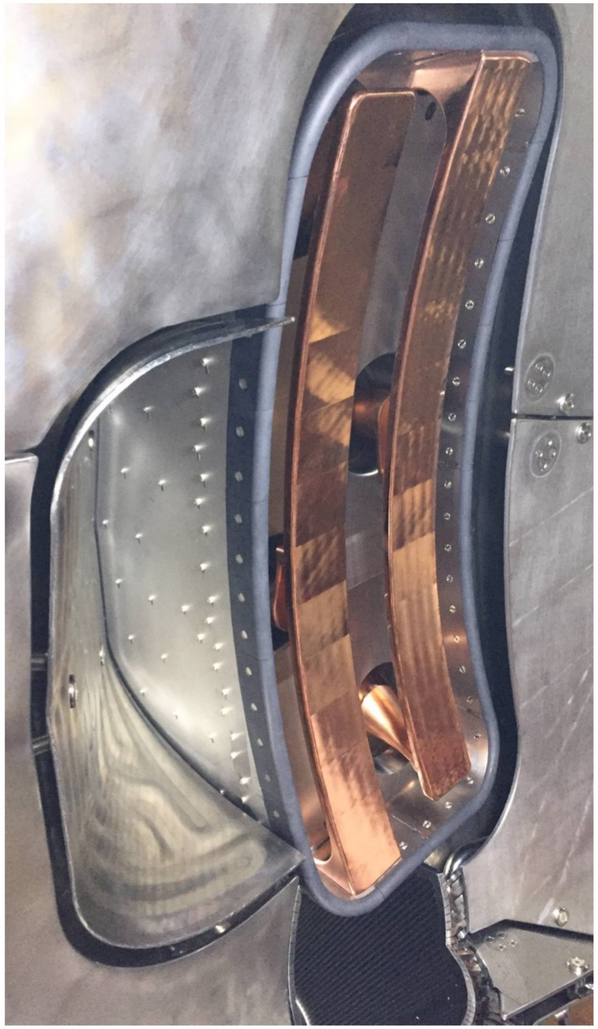
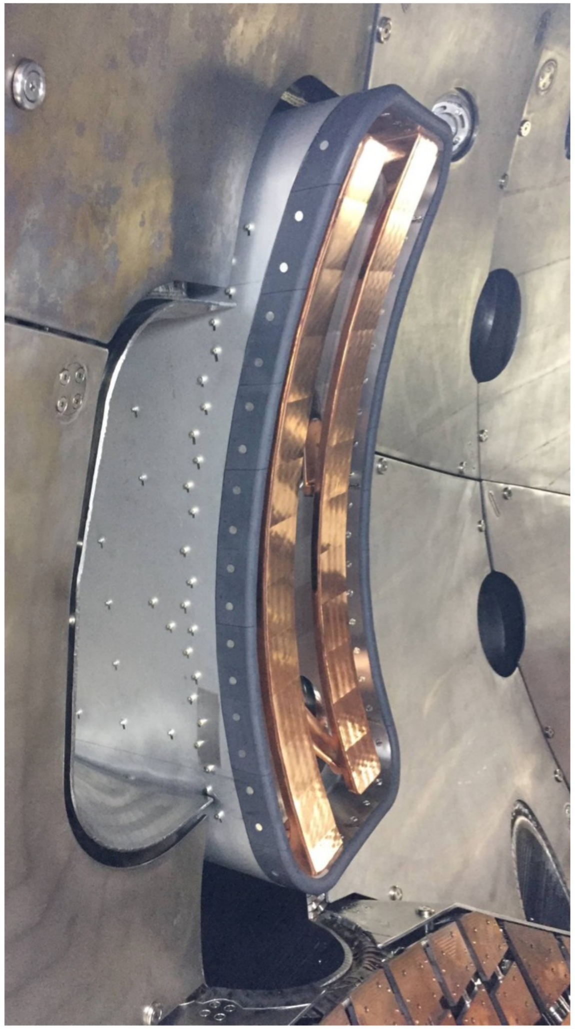
$k_{||}$ spectrum of the W7-X ICRH antenna



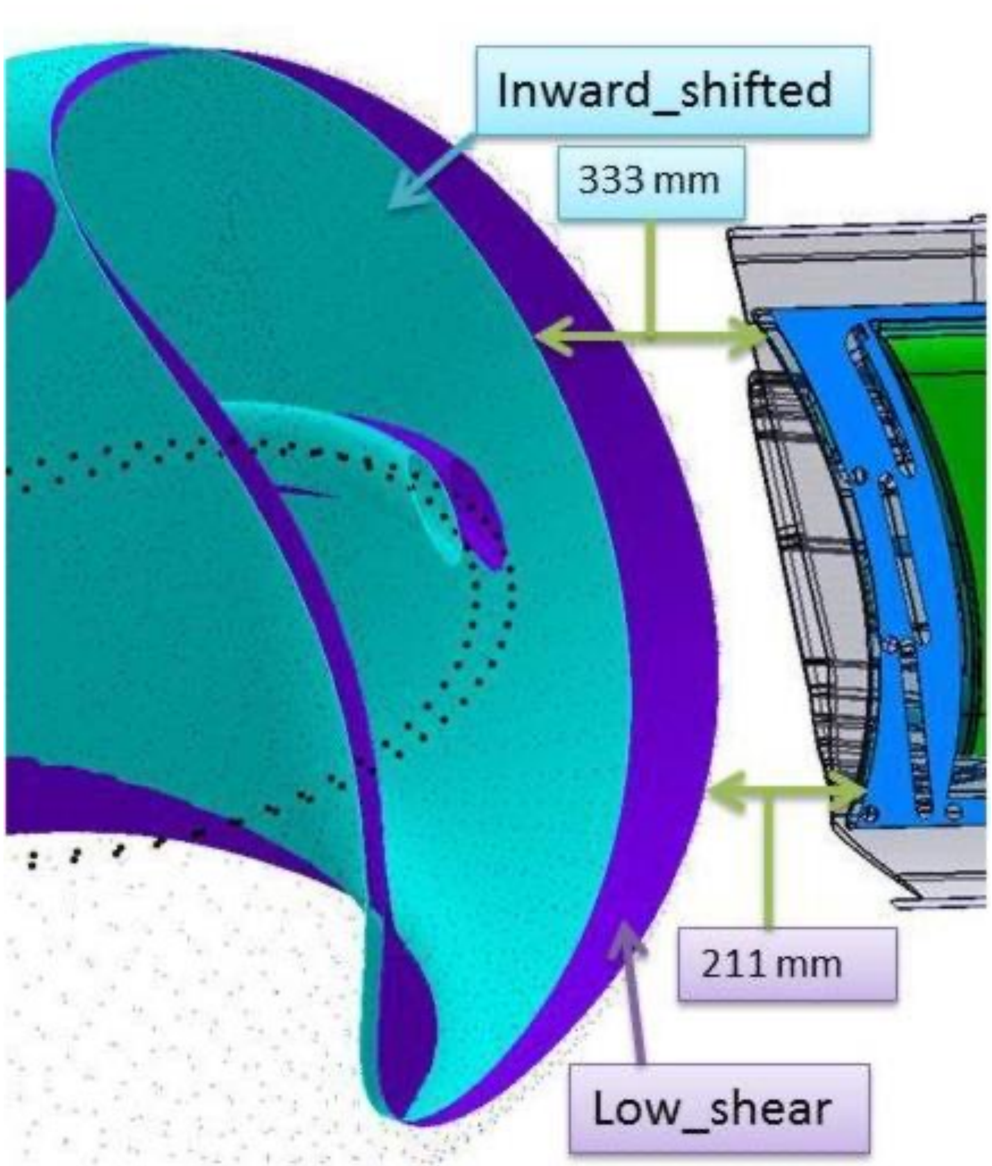
Phasing	Dominant $k_{||}$ (m^{-1})
0 0	3.6** 18
0 ±π/2	6.2* 14
0 π	10

** coaxial modes strongly excited
* coaxial modes somewhat excited

Specific properties of the ICRH antenna for Wendelstein 7-X

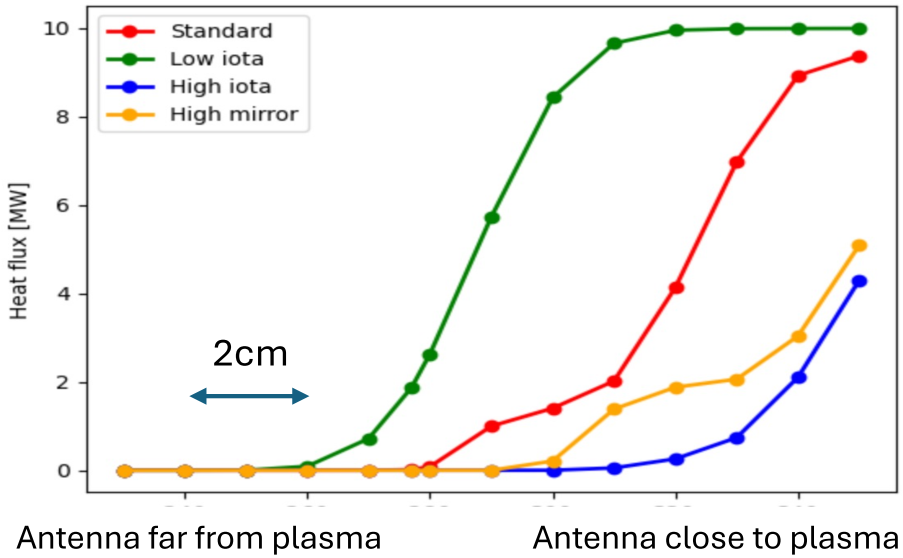
  

To improve coupling to all magnetic configurations in W7-X
➤ Radial displacement of the antenna



Radial displacement of the antenna: up to 35cm

Thermal load on the antenna: steep increase as a function of the radial position



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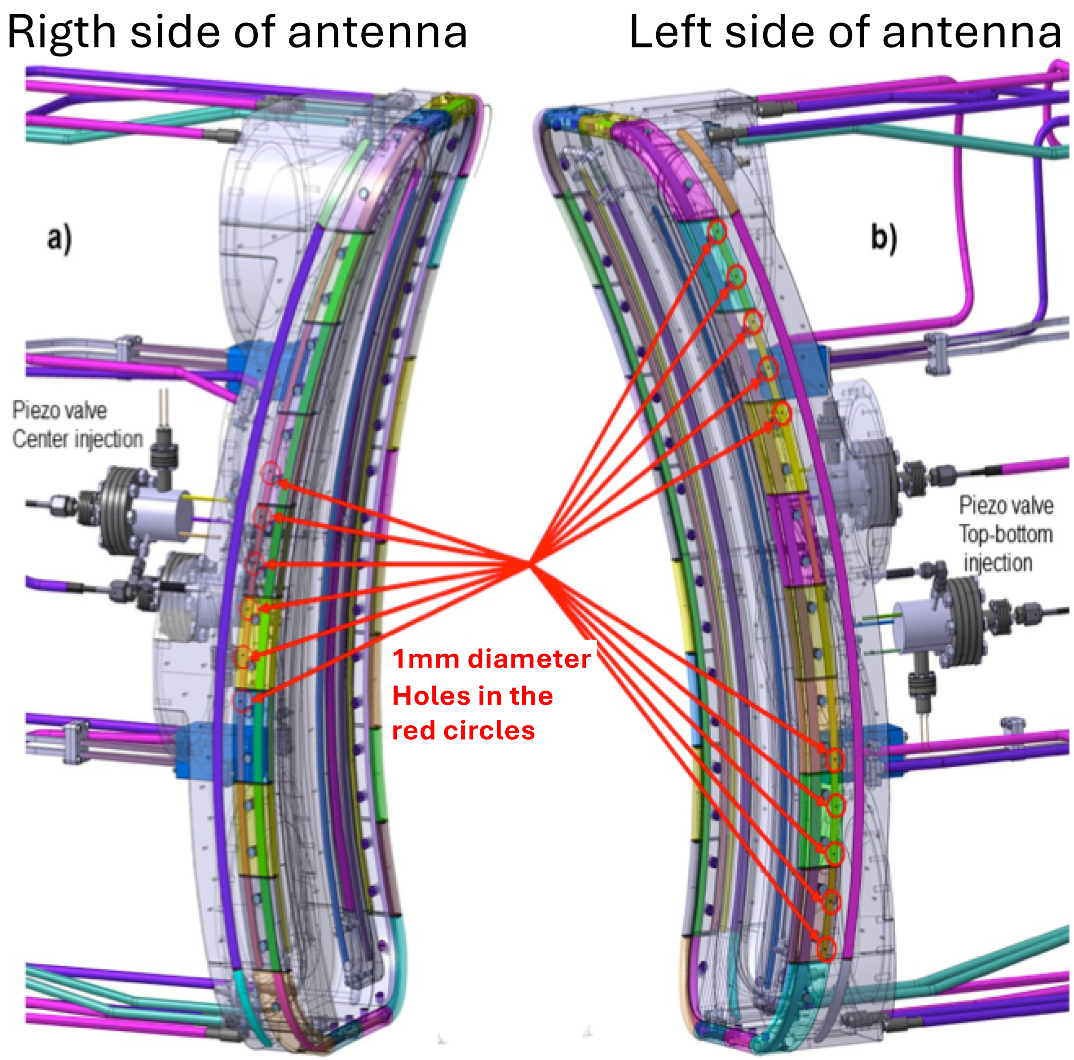
Improving the coupling for all magnetic configurations ➛ local gas puffing at the antenna

"High Iota"
Gas puff in equatorial gap

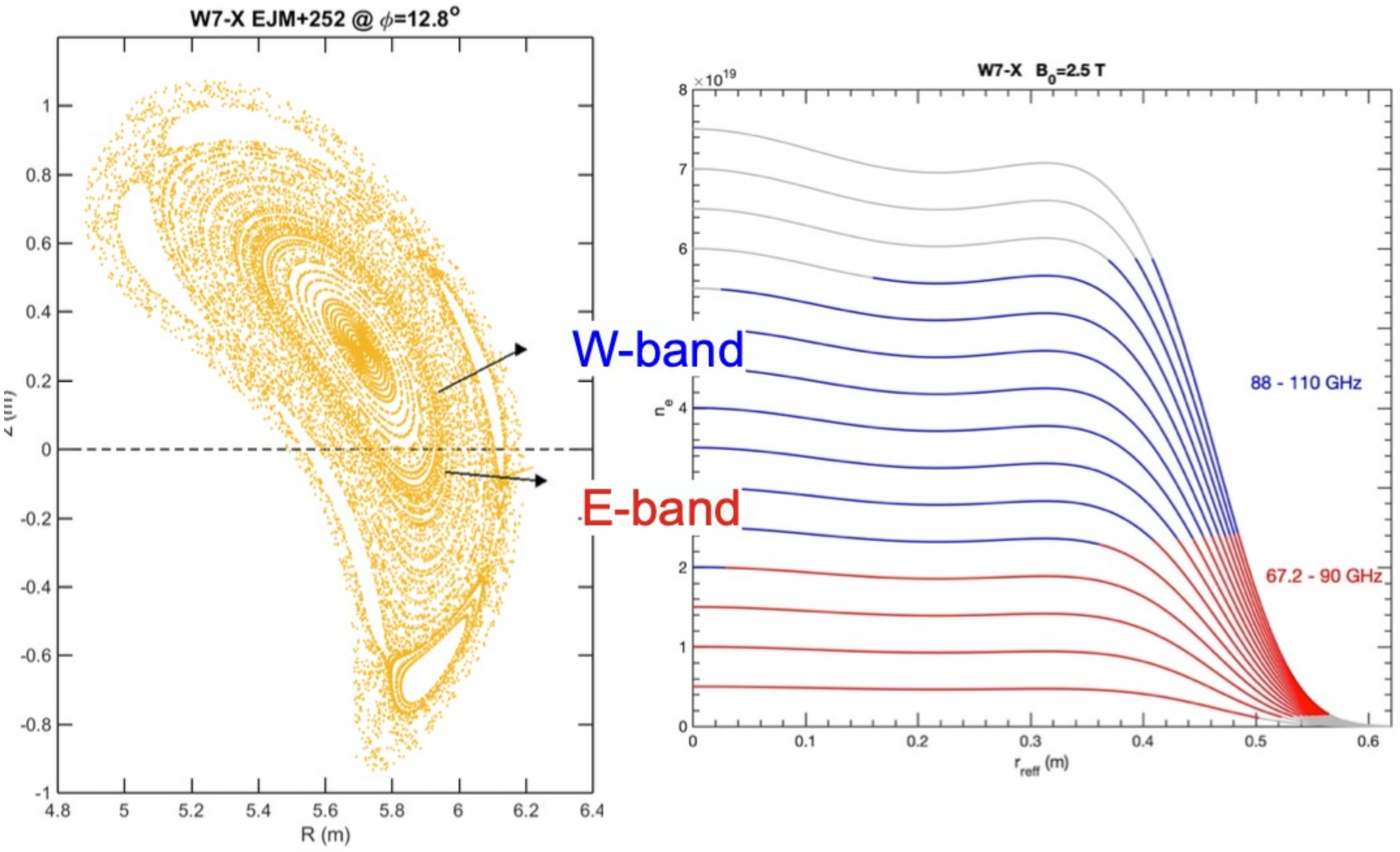


"Low iota"
Gap
Above and below

Maximal flux: 6mb liter/sec ~ 5 10^{20} particles/sec
(for sum of all holes on one side)

Profile measurements in front of antenna with reflectometry

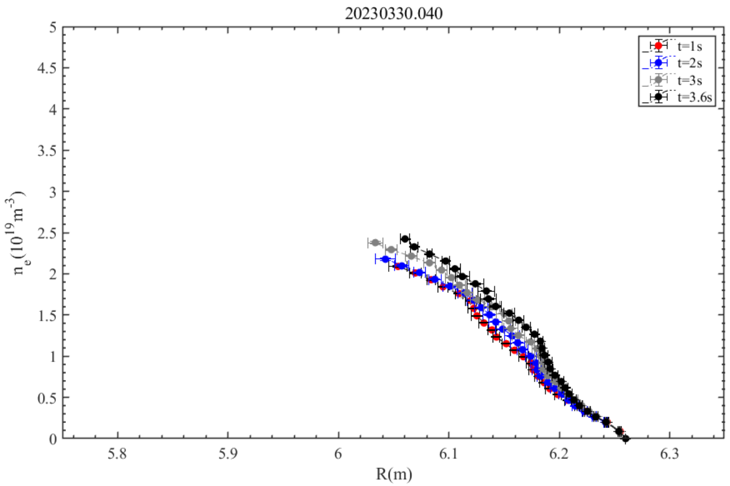
Use of X-Mode-Polarisation in the E- and W-Band at 2,5 T
To measure the density profile in front of the antenna



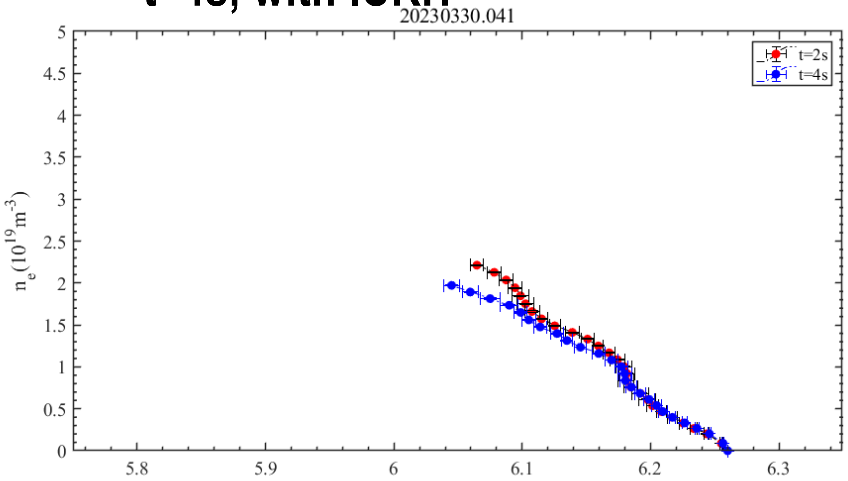
Electron density profile recorded for 2.5ms (50µs one profile) for a time interval of 100ms

Example density profiles before antenna measured during ICRH

Density up to 3 10^{19} m^{-3}
t=3s/3.6s, with ICRH



Density up to 2.5 10^{19} m^{-3}
t=4s, with ICRH



Density up to 2.5 10^{19} m^{-3}
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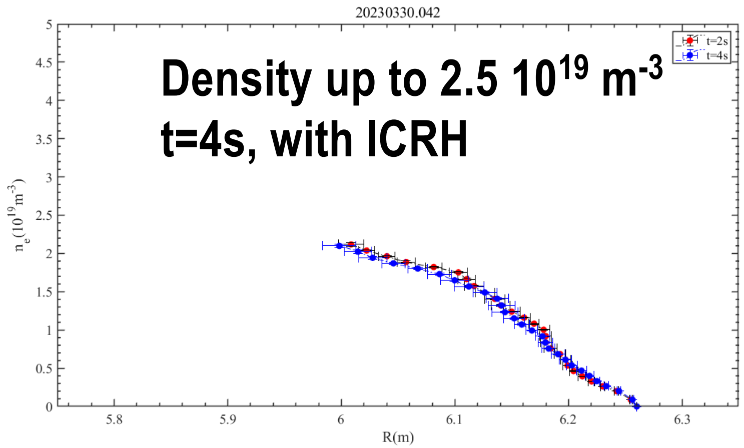
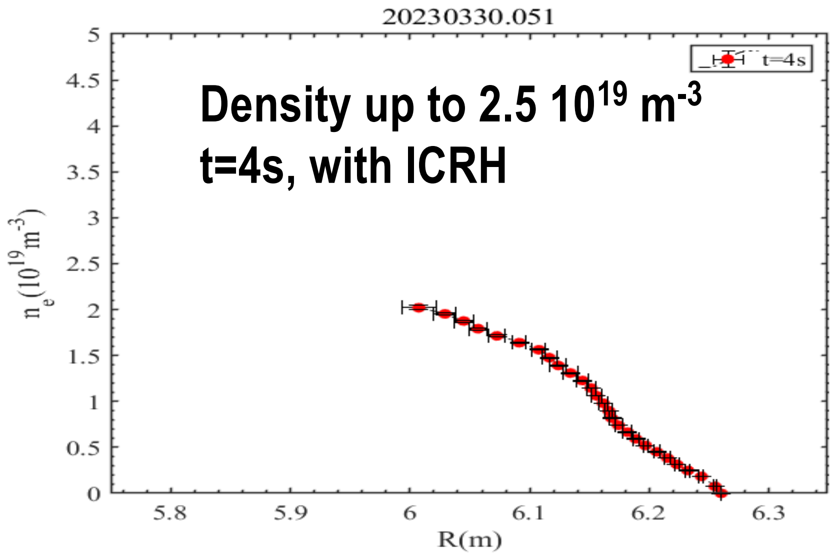


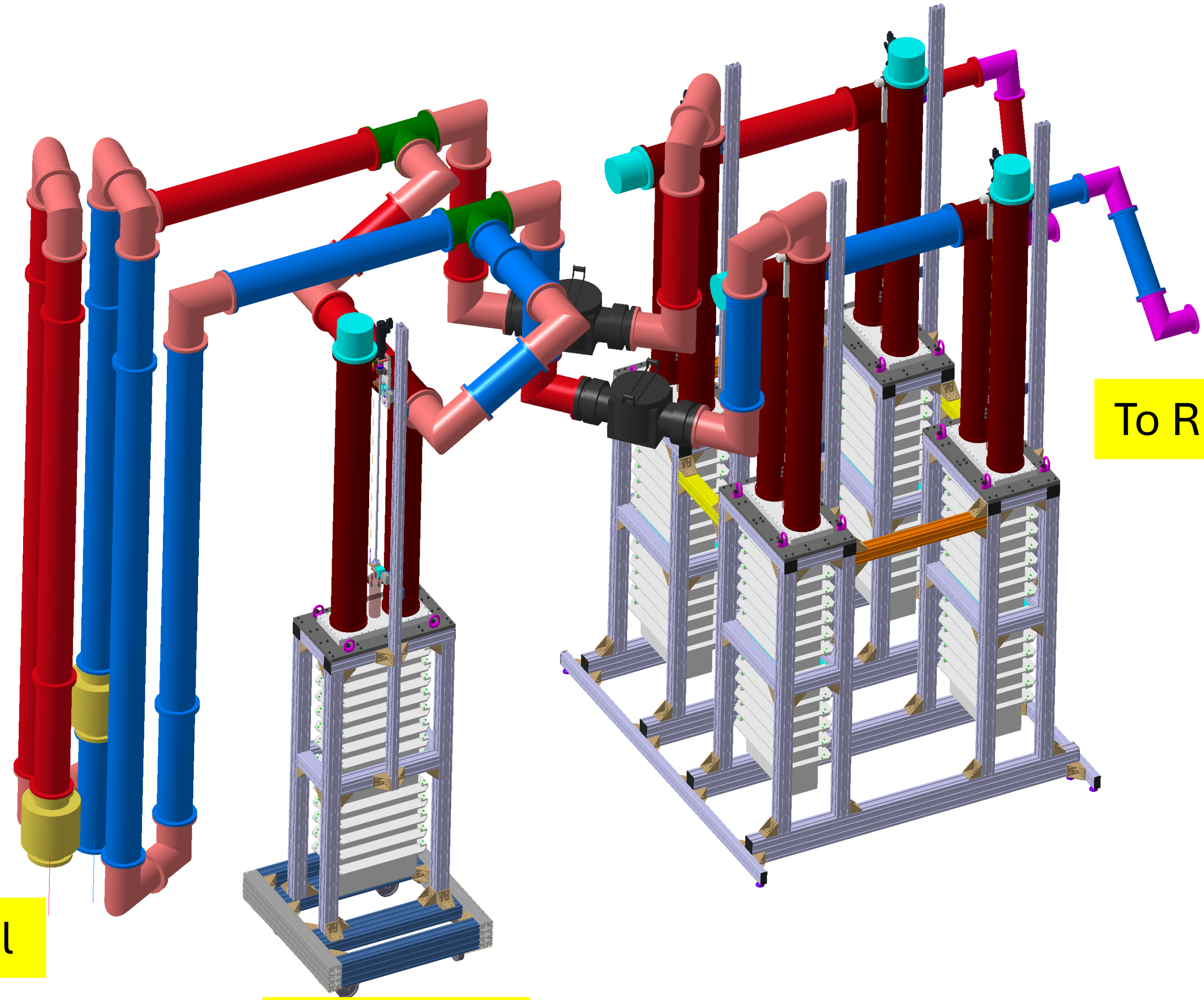
Density up to 2.5 10^{19} m^{-3}
t=4s, with ICRH



The reflectometer is also available outside ICRH operations

Details of matching system

Flexible system for 1 or 2 generators with elimination of cross-coupling
Cross-coupling between straps ~ Sin($\Delta\Phi$)

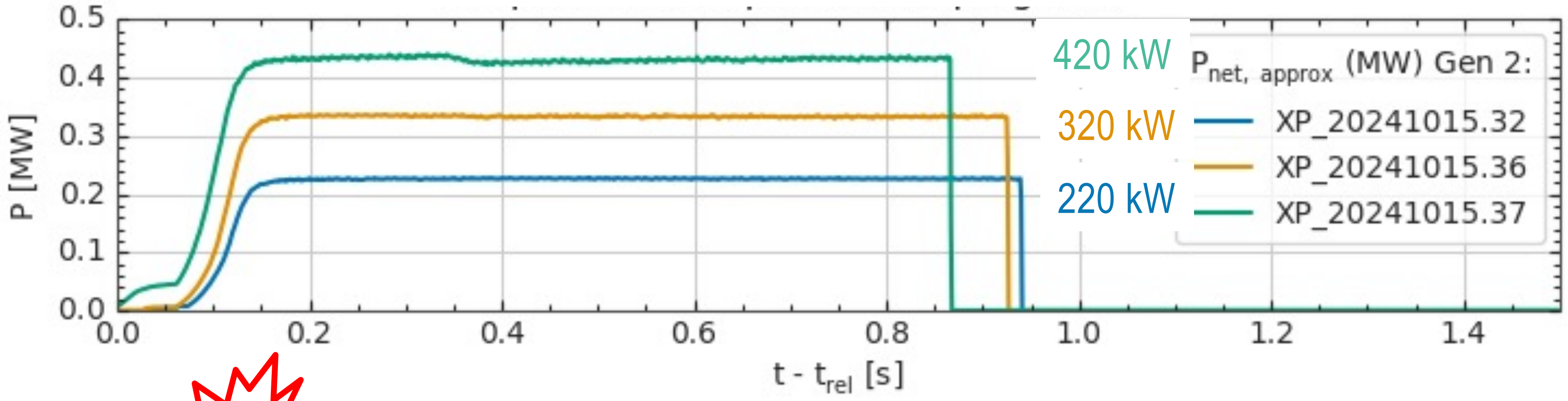


Cross-coupling maximum for $\Delta\Phi$ = +-90°
Cross-coupling minimal for $\Delta\Phi$ = 0°, 180°

Demonstration of technical capabilities in OP2.2

400 kW, ~1 s : plasma startup realized

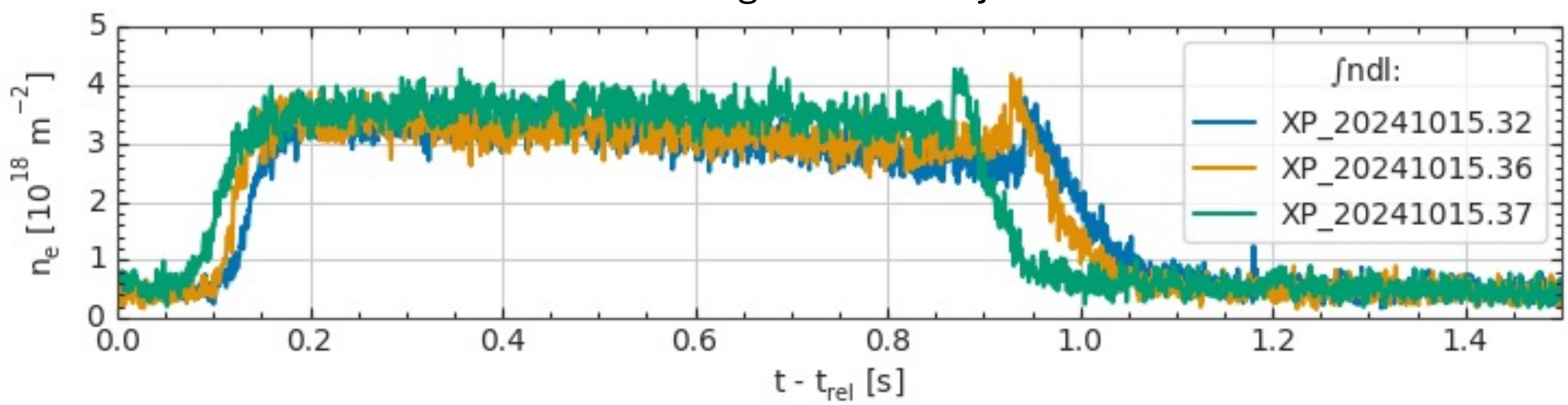
Power at antenna



NEW

Monopole configuration, 25MHz, 1.7T, H plasma

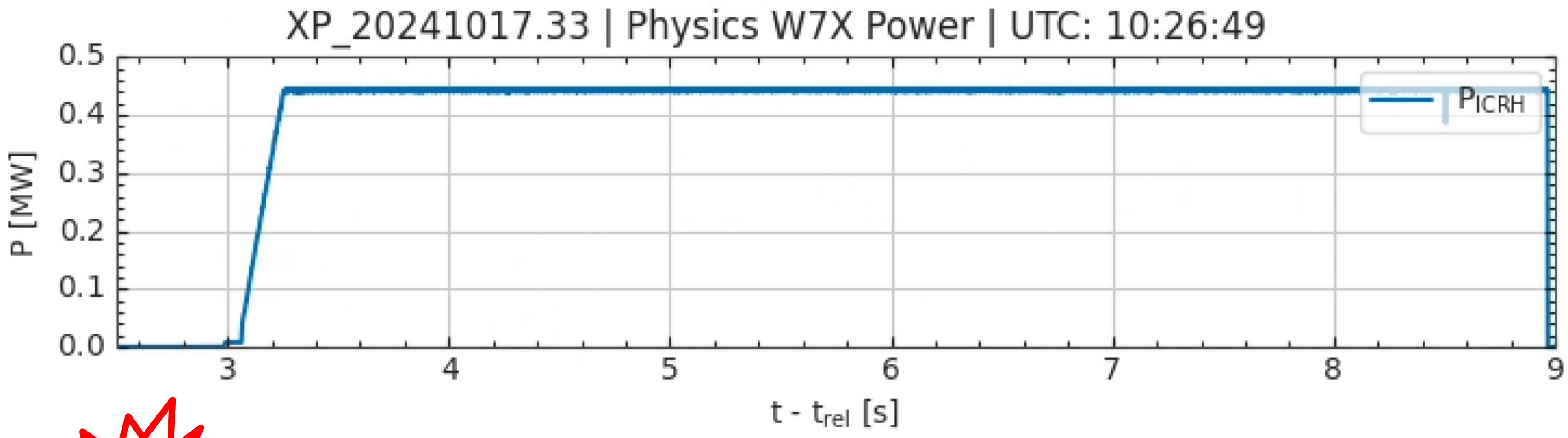
Line integrated density



400 kW, ~1s : plasma startup realized !

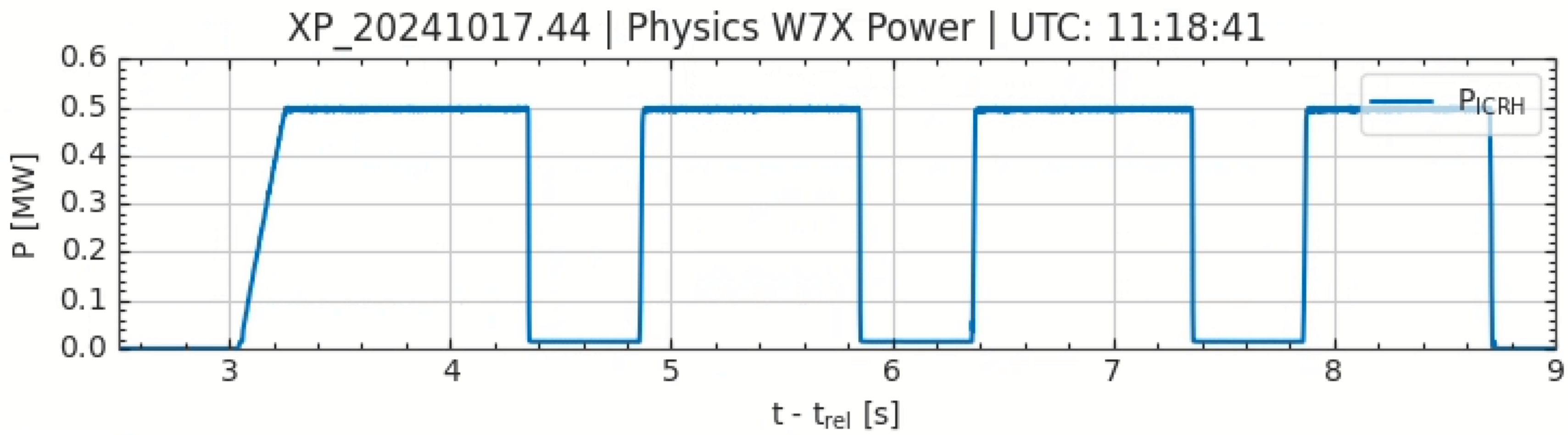
450 kW ICRH power for 6s, without breakdowns at antenna

450kW constant ICRH power launched for 6s

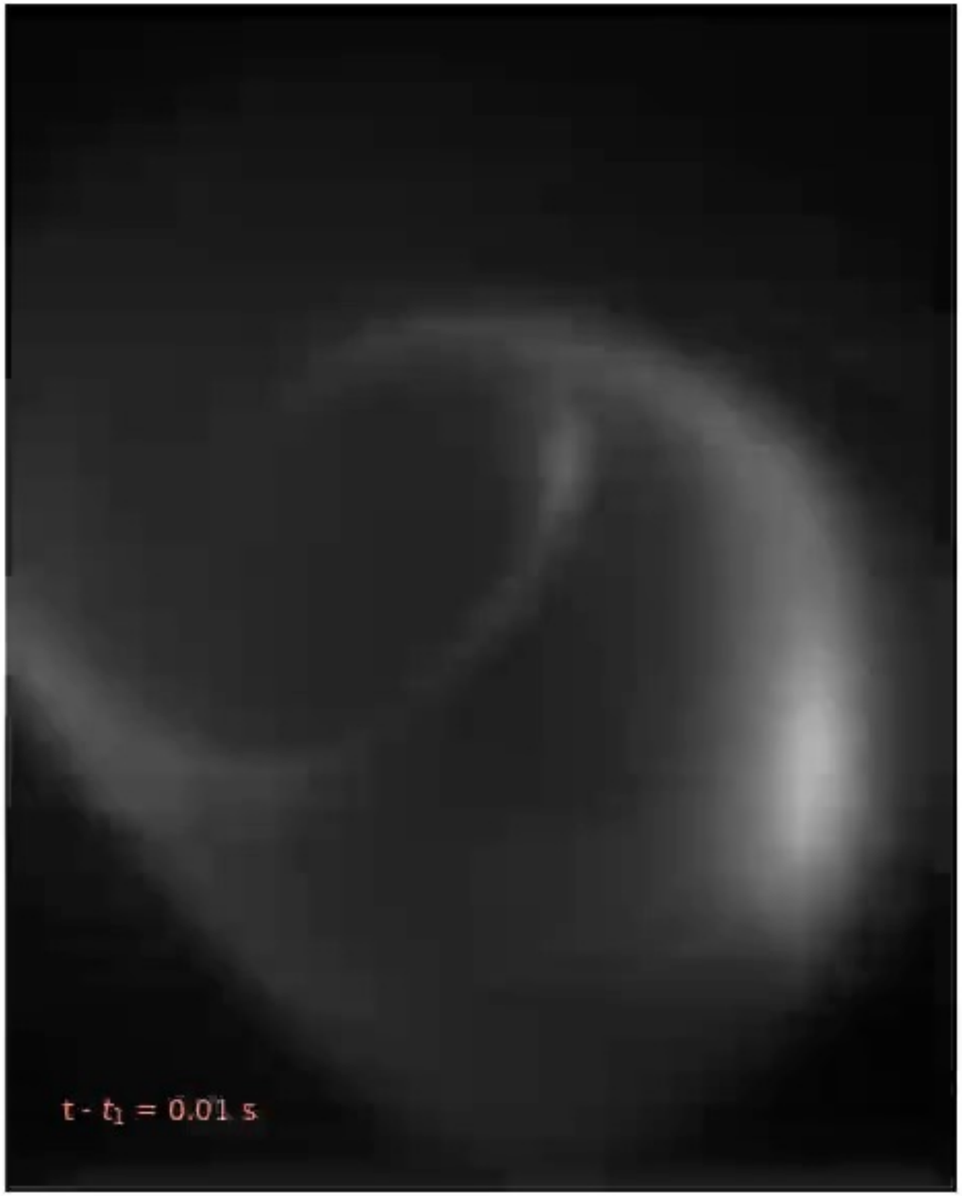


Dipole configuration, 25MHz, 2.5T, H plasma with ^{3}He

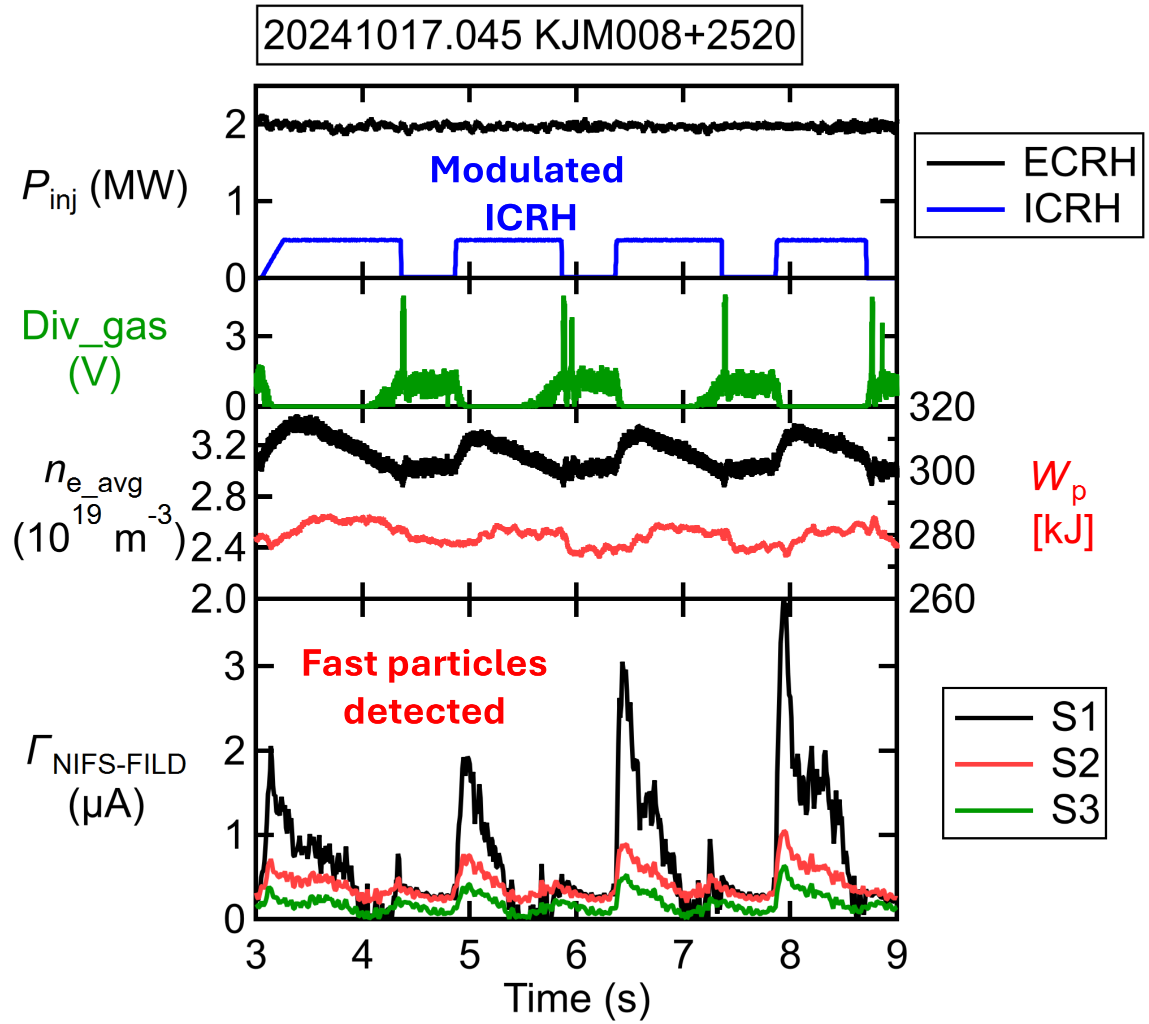
Power modulation at antenna (500kW)

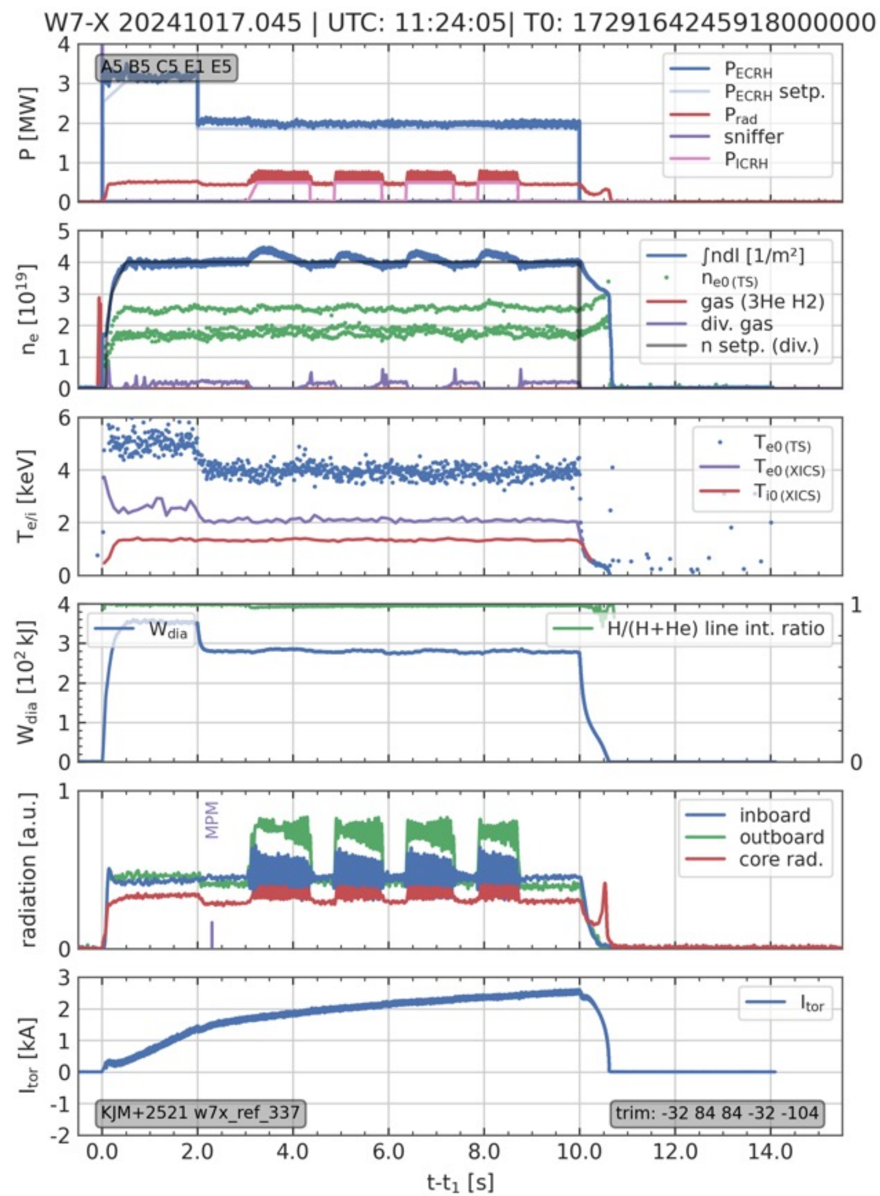


500kW ICRH power modulation during 9s



Fast particles generated with ICRH in W7-X



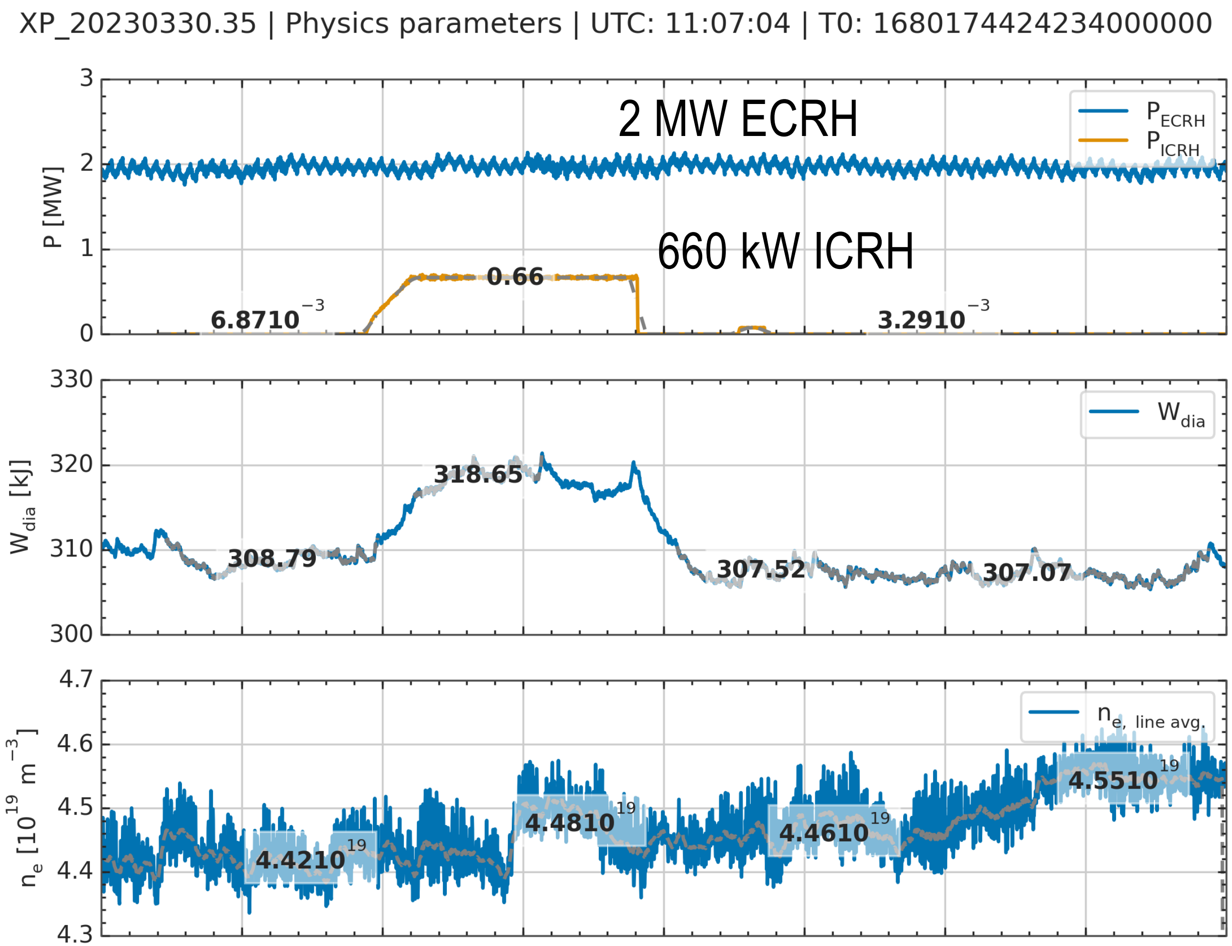


But no clear increase in stored energy or plasma temperatures

Acknowledgement : Kunihiro Ogawa , NIFS, Japan
IPP colleagues involved in FILD project

But heating (albeit small) seen in ICRH experiments before (Feb/Mar '23)

With single strap (~monopole phasing) antenna



Increase in the energy stored in the plasma

At constant density

Heating and fast particle generation with ICRH in toroidal systems

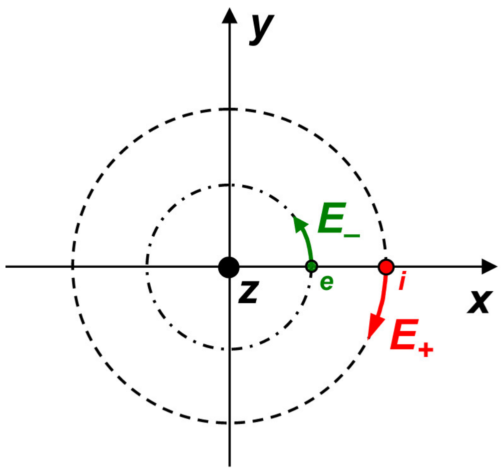
Heating in single and two ion plasmas

Correct polarization determines wave absorption

$$\omega = N\omega_{ci}: \qquad P_{\mathrm{abs,i}} \propto \left| E_+ J_{N-1}(k_\perp \rho_\mathrm{L}) + E_- J_{N+1}(k_\perp \rho_\mathrm{L}) \right|^2$$

cold plasma, N=1: $k_\perp \rho_\mathrm{L} \ll 1: \quad J_0 \approx 1, \; J_N \propto (k_\perp \rho_L)^N \ll 1$ $\rightarrow P_{abs,i} \propto |E_+|^2$

E_+ and E_- components of RF electric field



E_+ ➛ ion rotation direction

E_- ➛ electron rotation direction

Heating in single and two ion plasmas

Correct polarization determines wave absorption

$$\omega = N\omega_{ci} : \qquad P_{\mathrm{abs,i}} \propto \left| E_+ J_{N-1}(k_\perp \rho_\mathrm{L}) + E_- J_{N+1}(k_\perp \rho_\mathrm{L}) \right|^2$$

cold plasma, N=1: $\quad k_\perp \rho_\mathrm{L} \ll 1 : \quad J_0 \approx 1, \; J_N \propto (k_\perp \rho_L)^N \ll 1 \quad \rightarrow P_{abs,i} \propto |E_+|^2$

From Maxwell equations:
Electric field polarization at resonance position

depends on plasma composition

$$\left| \frac{E_+}{E_-} \right| = \left| \frac{\omega - \omega_{ci}}{\omega + \omega_{ci}} \right|$$

ω = frequency applied at the antenna

Heating in single and two ion plasmas

Correct polarization determines wave absorption

$$\omega = N\omega_{ci}: \qquad P_{\mathrm{abs,i}} \propto \left| E_+ J_{N-1}(k_\perp \rho_L) + E_- J_{N+1}(k_\perp \rho_L) \right|^2$$

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From Maxwell equations:
Electric field polarization at resonance position

$$\left|\frac{E_+}{E_-}\right| = \left|\frac{\omega - \omega_{ci}}{\omega + \omega_{ci}}\right|$$

ω = frequency applied at the antenna

depends on plasma composition

1. Single ion plasma i heating does not work at $\omega = \omega_{ci}$

$$\left|\frac{E_+}{E_-}\right| \simeq \left|\frac{\omega_{ci} - \omega_{ci}}{\omega_{ci} + \omega_{ci}}\right| \simeq 0$$

2. Need two ions in plasma e.g. minority heating (H)-D; minority at a few %: $\omega = \omega_{cH}$

$$\left|\frac{E_+}{E_-}\right| \simeq \left|\frac{\omega_{cH} - \omega_{cD}}{\omega_{cH} + \omega_{cD}}\right| = \left|\frac{2\omega_{cD} - \omega_{cD}}{2\omega_{cD} + \omega_{cD}}\right| = \frac{1}{3}$$

3. Harmonic heating $\omega = N\omega_{ci}$ (e.g. second harmonic heating)

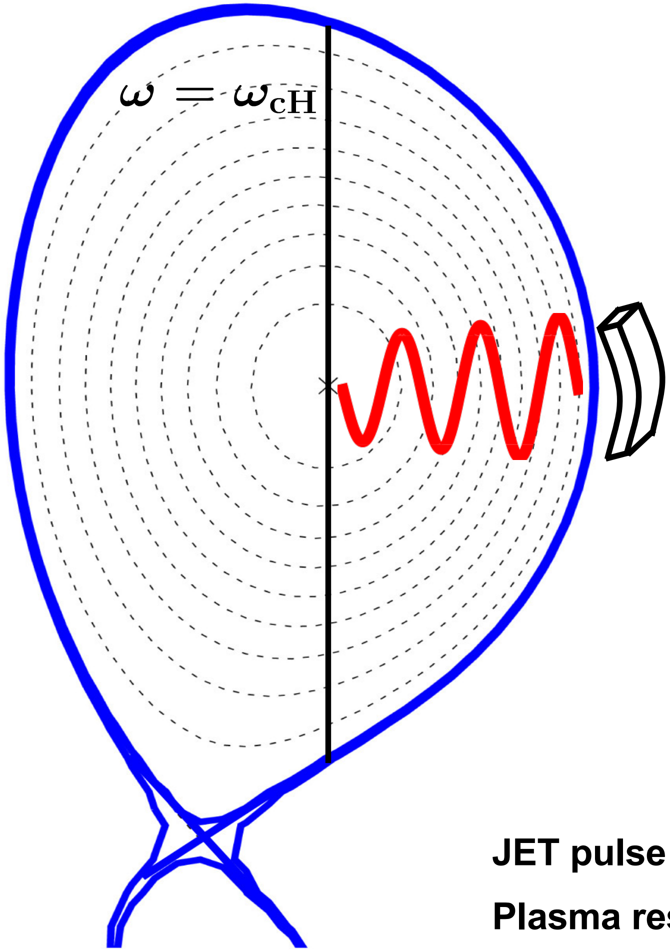
$$\left|\frac{E_+}{E_-}\right| \simeq \left|\frac{N\omega_{ci} - \omega_{ci}}{N\omega_{ci} + \omega_{ci}}\right| = \frac{N-1}{N+1}$$

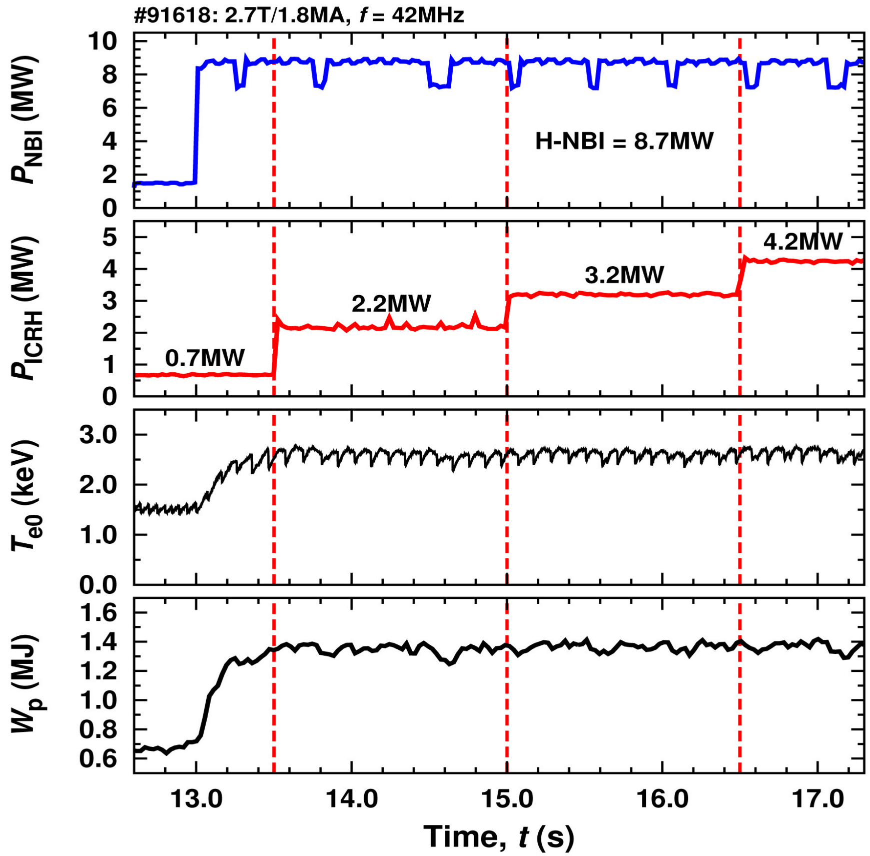
J.Ongena et al., Plasma Phys. Control. Fusion 59 054002 (2017)

Fundamental heating of single-ion species plasmas does not work

Example :

Hydrogen plasmas ($n_H/n_e \approx 100\%$)





JET pulse #91618, ICRH power: 0.7MW → 2.2MW → 3.2MW → 4.2MW

Plasma response: $\Delta T_e \approx 0$, $\Delta W_p \approx 0$

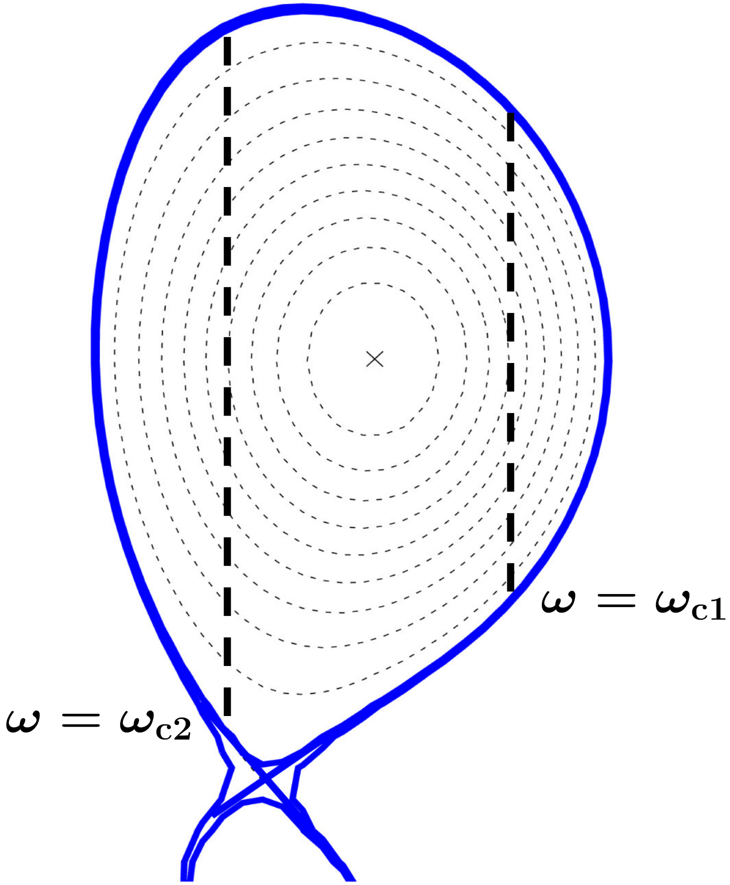
$E_+ \sim 0$, thus as $P_{abs,I} \sim |E_+|^2 \sim 0$, i.e. heating effects are possible !

Fundamental ICRF heating of single ion plasmas DOES NOT WORK

Physics of ICRF heating at the fundamental frequency of the minority in two ion plasmas

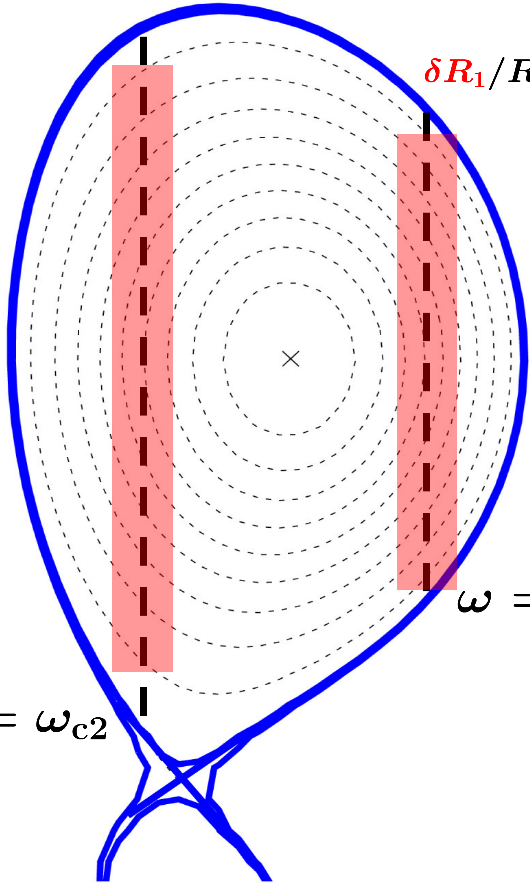
Importance of the ion-ion hybrid layer and its location in the plasma cross-section

Heating scenario's in two ion plasmas



- **Two ion species $(Z/A)_1$ and $(Z/A)_2$**
- **Two ion cyclotron layers:**
  $\omega \approx \omega_{c1}$ **and** $\omega \approx \omega_{c2}$

Heating scenario's in two ion plasmas



- Two ion species $(Z/A)_1$ and $(Z/A)_2$
- Two ion cyclotron (IC) layers:
  $\omega \approx \omega_{c1}$ and $\omega \approx \omega_{c2}$
- Every IC layer has a natural width $\delta R_{1,2}$

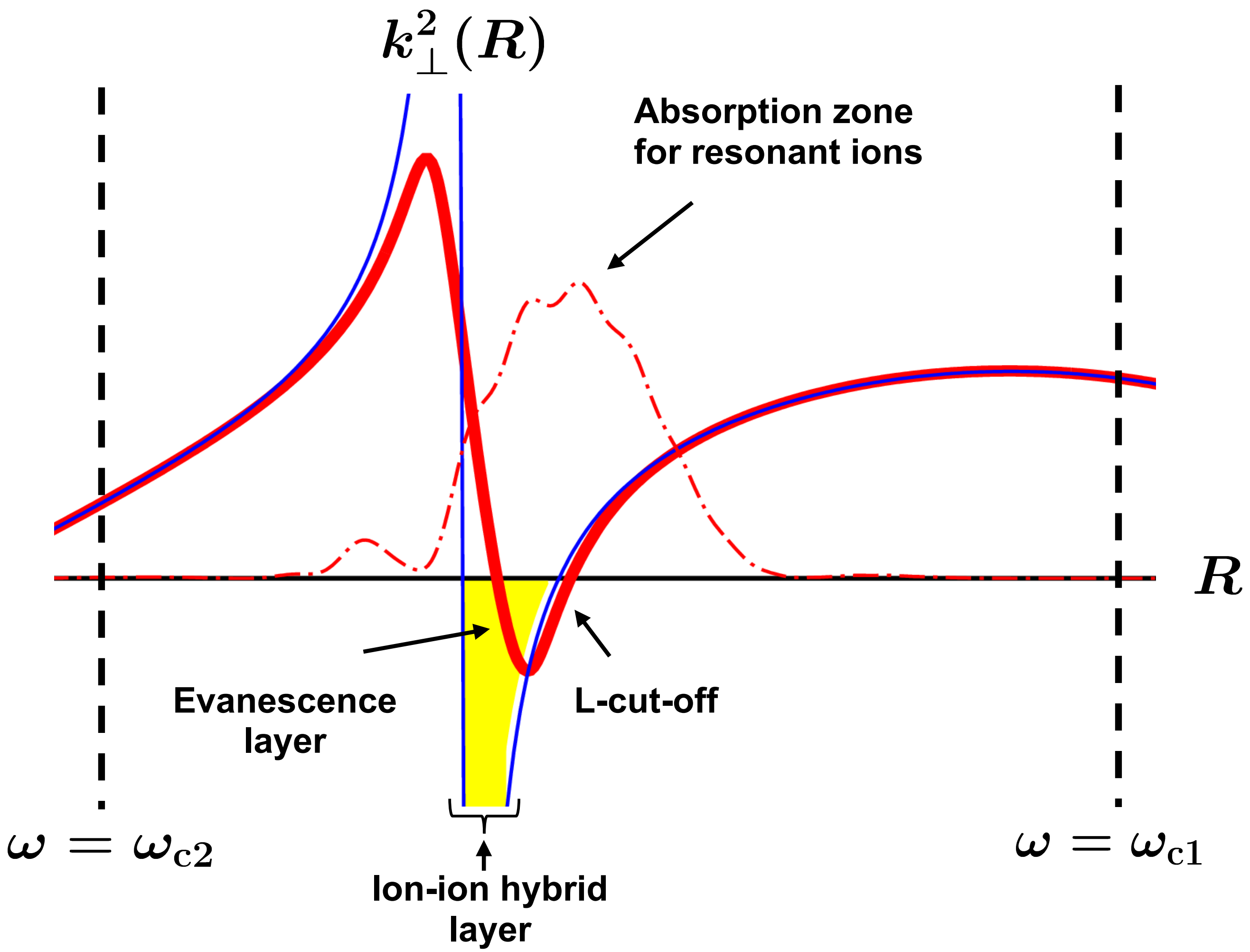
For particles with T~ 2 keV in W7-X
$\delta R_{1,2}$ = few cm

Ye.O. Kazakov et al., Nucl. Fusion 55 032001 (2015)

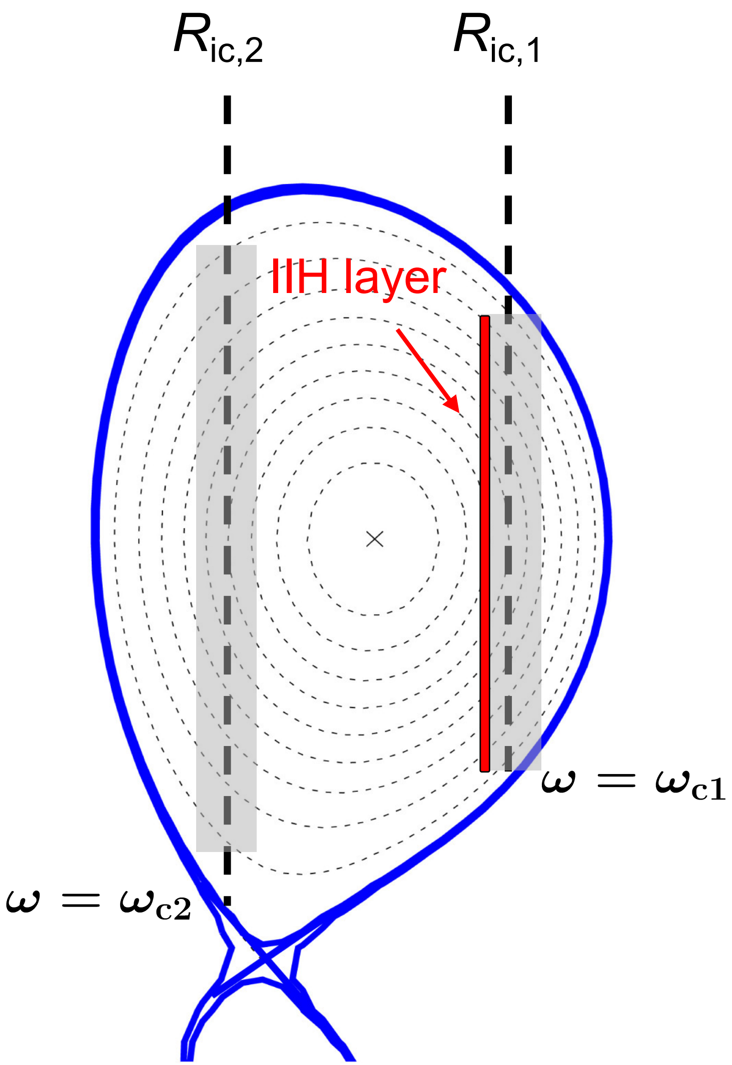
Presence of "ion-ion hybrid layer" in two ion plasmas

"Ion-ion hybrid layer" or IIH: short for the combination of L-cutoff and associated evanescence zone

- ➛ Located in between the two resonance layers
- ➛ Polarisation of RF electric field is mostly E_+: ideal for heating ions



Heating scenario's in two ion plasmas



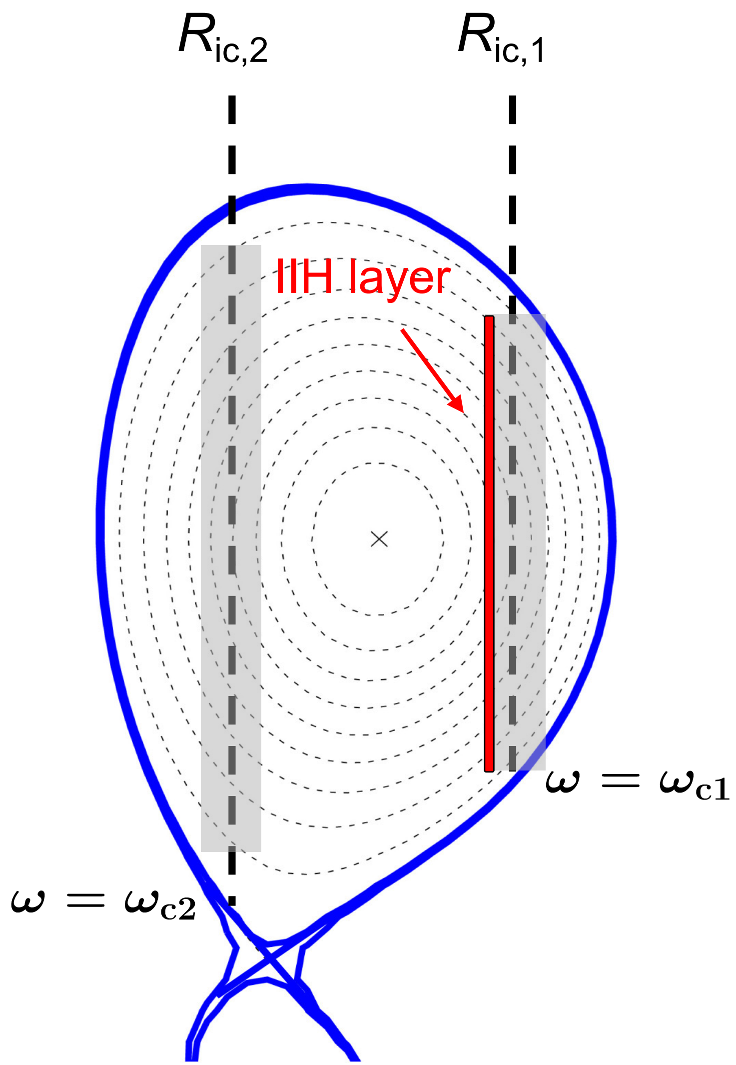
- ✓ **N=1: Ion absorption due to E_+**

$$P_{abs} \propto |E_+ J_0(k_\perp \rho_L) + E_- J_2(k_\perp \rho_L)|^2 \approx |E_+|^2$$

- ✓ **Ion-ion hybrid layer, with large E_+: in between $R_{ic,2}$ and $R_{ic,1}$**

Importance of presence of IIH:
RF electric field circularly polarized
in rotation direction of ions
➛ ideal for ion heating

Minority heating in two ion plasmas



- ✓ **N=1: Ion absorption due to E_+**

  $$P_{abs} \propto |E_+ J_0(k_\perp \rho_L) + E_- J_2(k_\perp \rho_L)|^2 \approx |E_+|^2$$

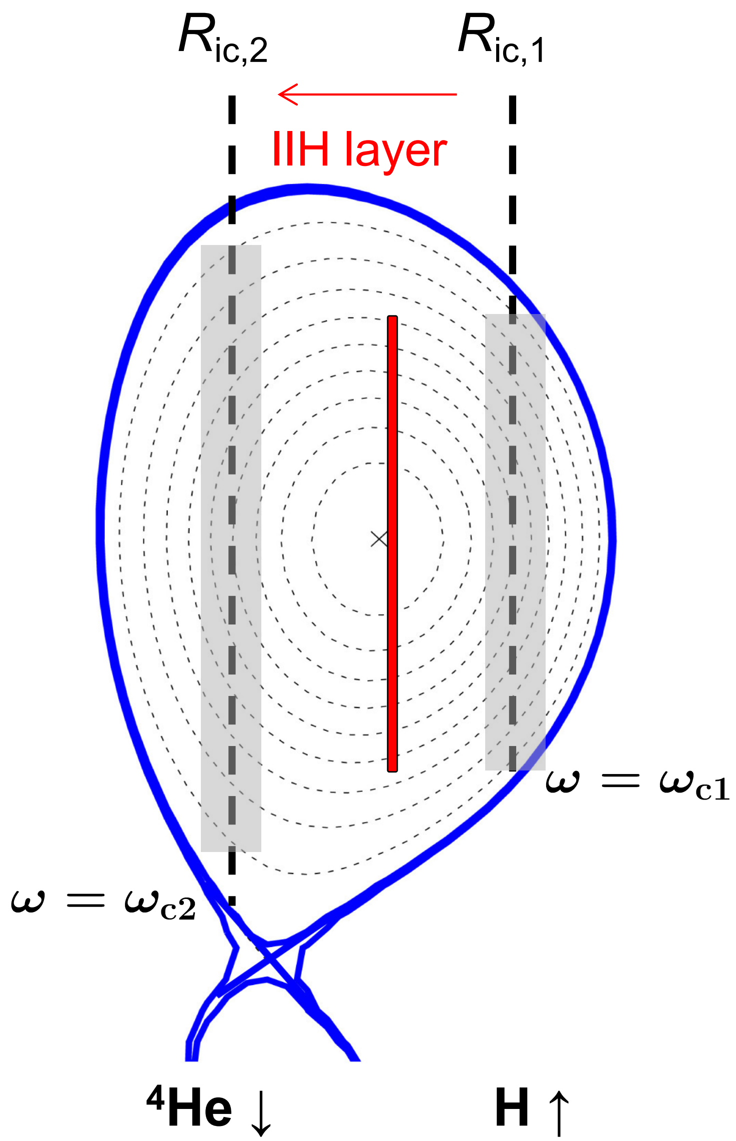
- ✓ **Ion-ion hybrid layer, with large E_+: in between $R_{ic,2}$ and $R_{ic,1}$**

- ✓ **At low minority concentration: ion-ion hybrid layer close to minority resonance layer**

- ✓ **Minority ions get efficiently heated**

Minority heating

Mode conversion (electron heating) in two ion plasmas



- ✓ **N=1: Ion absorption due to E_+**

  $$P_{abs} \propto |E_+ J_0(k_\perp \rho_L) + E_- J_2(k_\perp \rho_L)|^2 \approx |E_+|^2$$

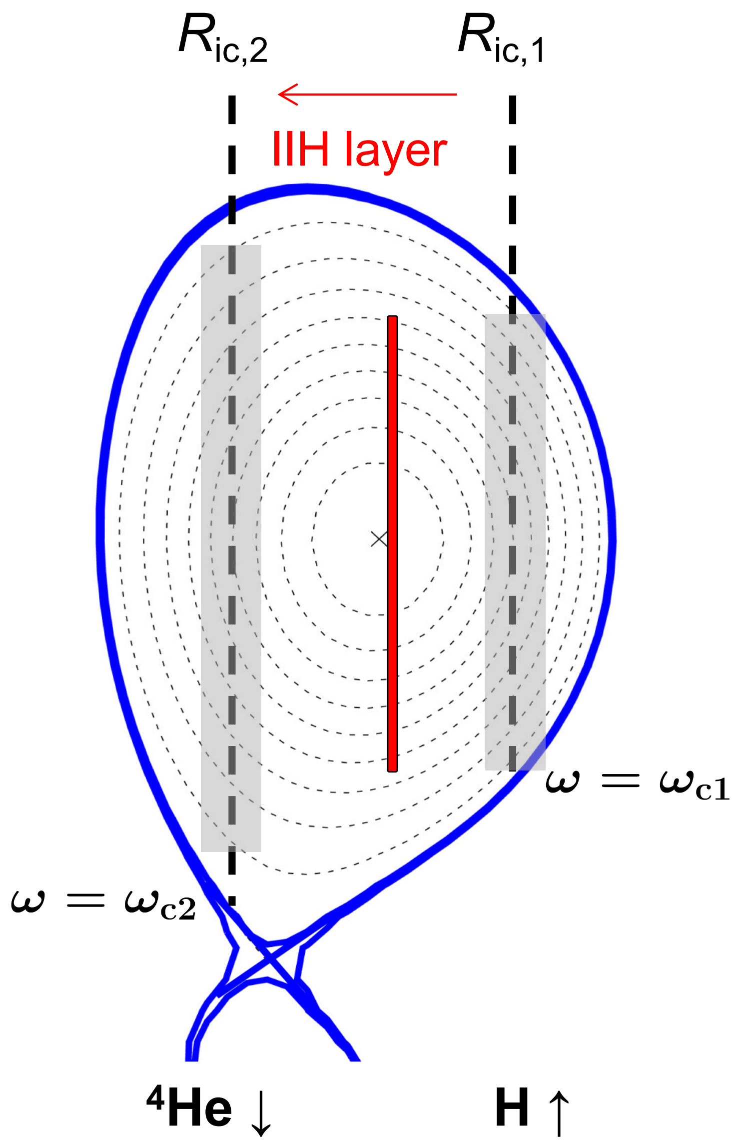
- ✓ **Ion-ion hybrid layer, with large E_+: in between $R_{ic,2}$ and $R_{ic,1}$**

- ✓ **At higher minority concentration: ion-ion hybrid layer moves away from minority resonance**

Electron heating
(by Mode Conversion)

3-ion heating in W7-X

The beautiful physics of 3-ion heating



- ✓ **N=1: Ion absorption due to E_+**

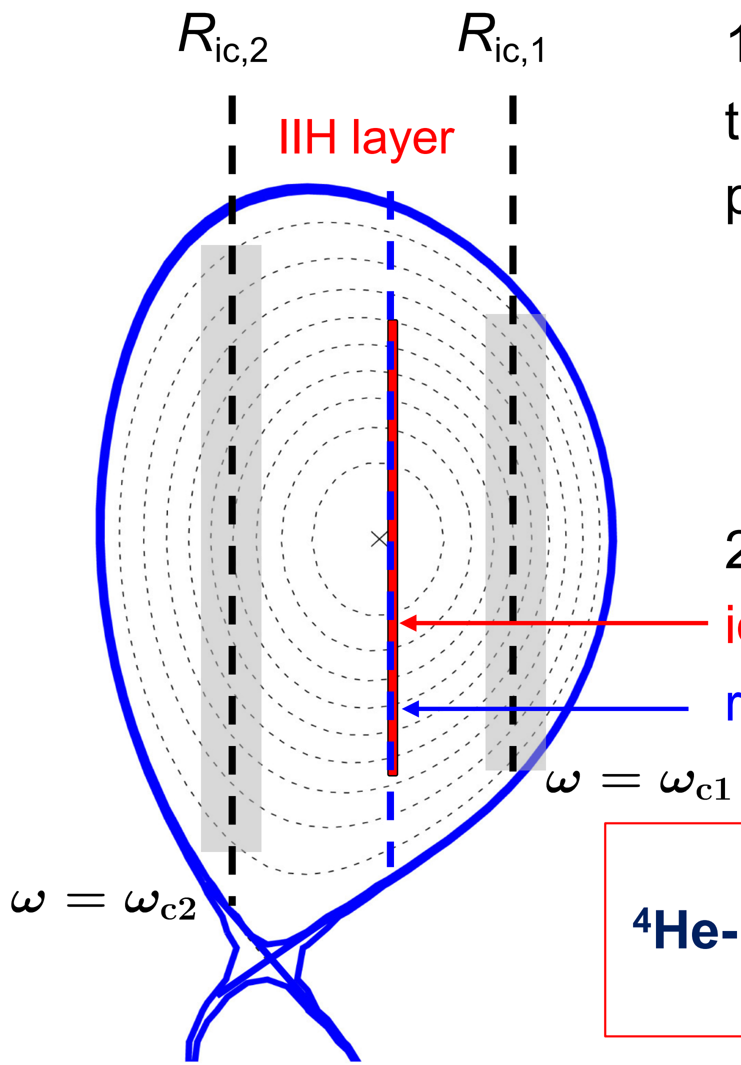
  $$P_{abs} \propto |E_+ J_0(k_\perp \rho_L) + E_- J_2(k_\perp \rho_L)|^2 \approx |E_+|^2$$

- ✓ **Ion-ion hybrid layer, with large E_+: in between $R_{ic,2}$ and $R_{ic,1}$**

- ✓ **At higher minority concentration ion-ion hybrid layer far away from minority resonance**

How to heat ions?

Use a suitable ion that resonates at the ion-ion hybrid layer



^{4}He ~15% **Z/A=1/2**

^{3}He ~1% **Z/A = 2/3**

H ~70% **Z/A =1**

1. Use a third ion with resonance layer at the ion-ion hybrid, i.e. in between the main plasma ion resonances:
   - ➢ $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$
   - ➢ Hence only ^{3}He is possible as third ion in ^{4}He-H two ion plasmas

2. Choose plasma composition such that the ion-ion hybrid coincides with the (fixed position) of the resonance layer of ^{3}He

In this way:
^{4}He-H ~ 15%:70% mixture maximizes E_+ polarization at the position of the ^{3}He resonance

*Ye.O. Kazakov et al, Nature Physics **13**, 973–978 (2017)*

Location of the IIH layer determined by plasma composition

Estimated shift between IIH layer and minority resonance

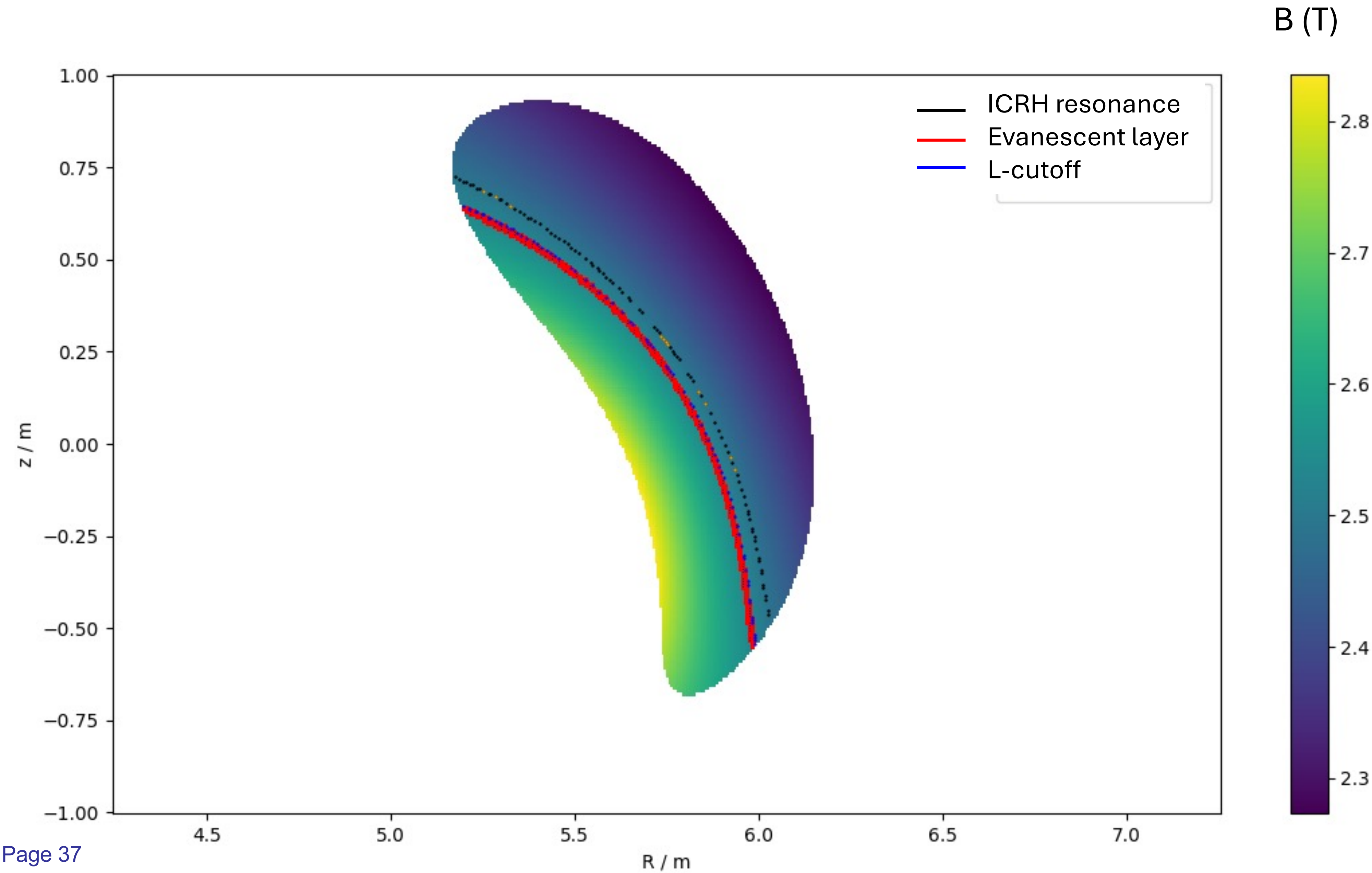
H-(^{3}He) scenario at 25MHz : ~ 3.3cm for every % of ^{3}He

^{4}He-(H) scenario at 37.5MHz : ~ 1.5 cm for every % of H

Illustration for the ^{4}He-(H) scenario with a 2D cold plasma model (C.Slaby)

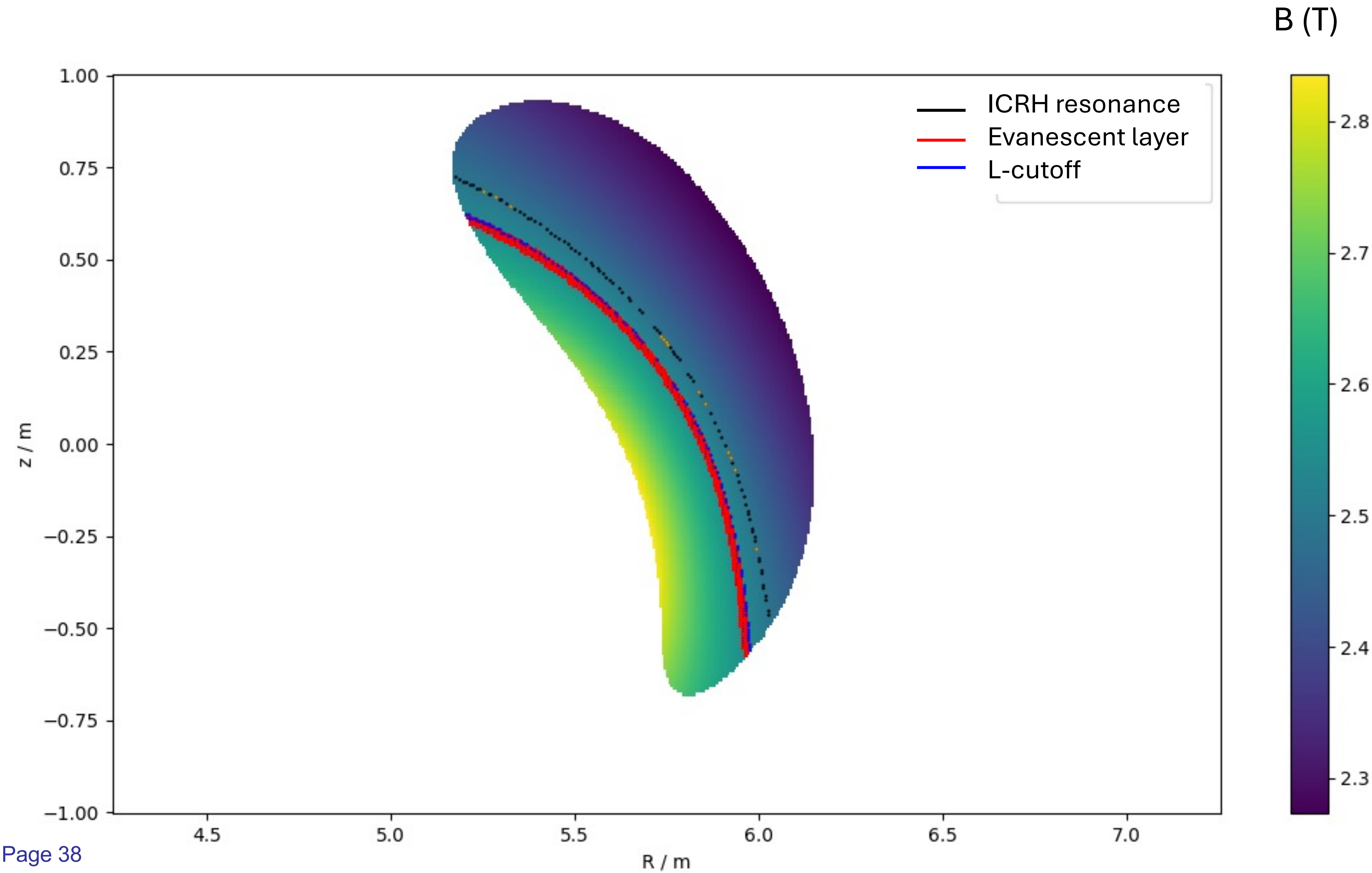
^{4}He-(H)

3% H


B (T)
ICRH resonance
Evanescent layer
L-cutoff
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
z / m
4.5
5.0
5.5
6.0
6.5
7.0
R / m
2.8
2.7
2.6
2.5
2.4
2.3

^{4}He-(H)

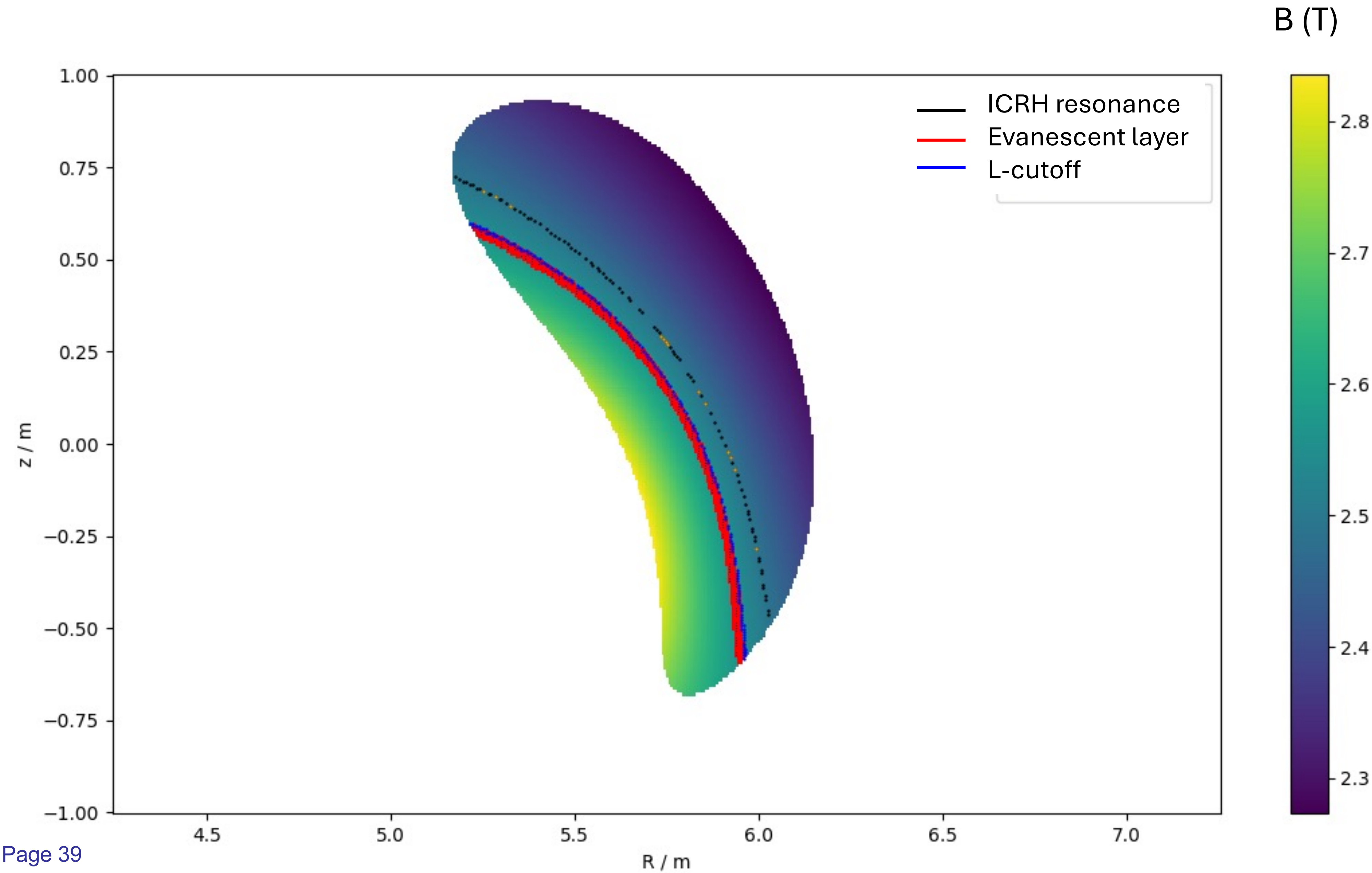
4% H



B (T)
ICRH resonance
Evanescent layer
L-cutoff
z / m
R / m
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
4.5
5.0
5.5
6.0
6.5
7.0
2.8
2.7
2.6
2.5
2.4
2.3

^{4}He-(H)

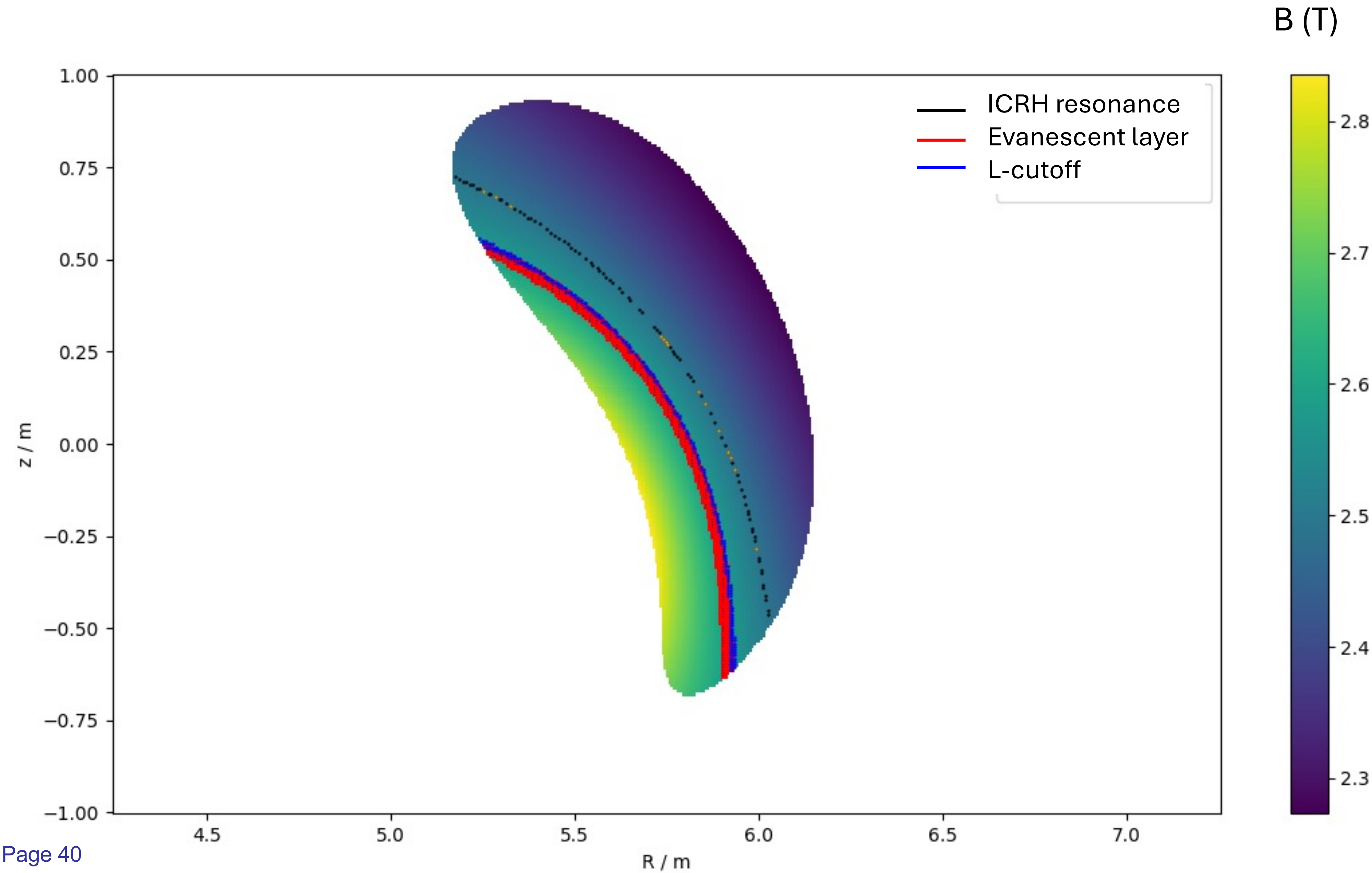
5% H



B (T)
ICRH resonance
Evanescent layer
L-cutoff
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
z / m
4.5
5.0
5.5
6.0
6.5
7.0
R / m
2.8
2.7
2.6
2.5
2.4
2.3

^{4}He-(H)

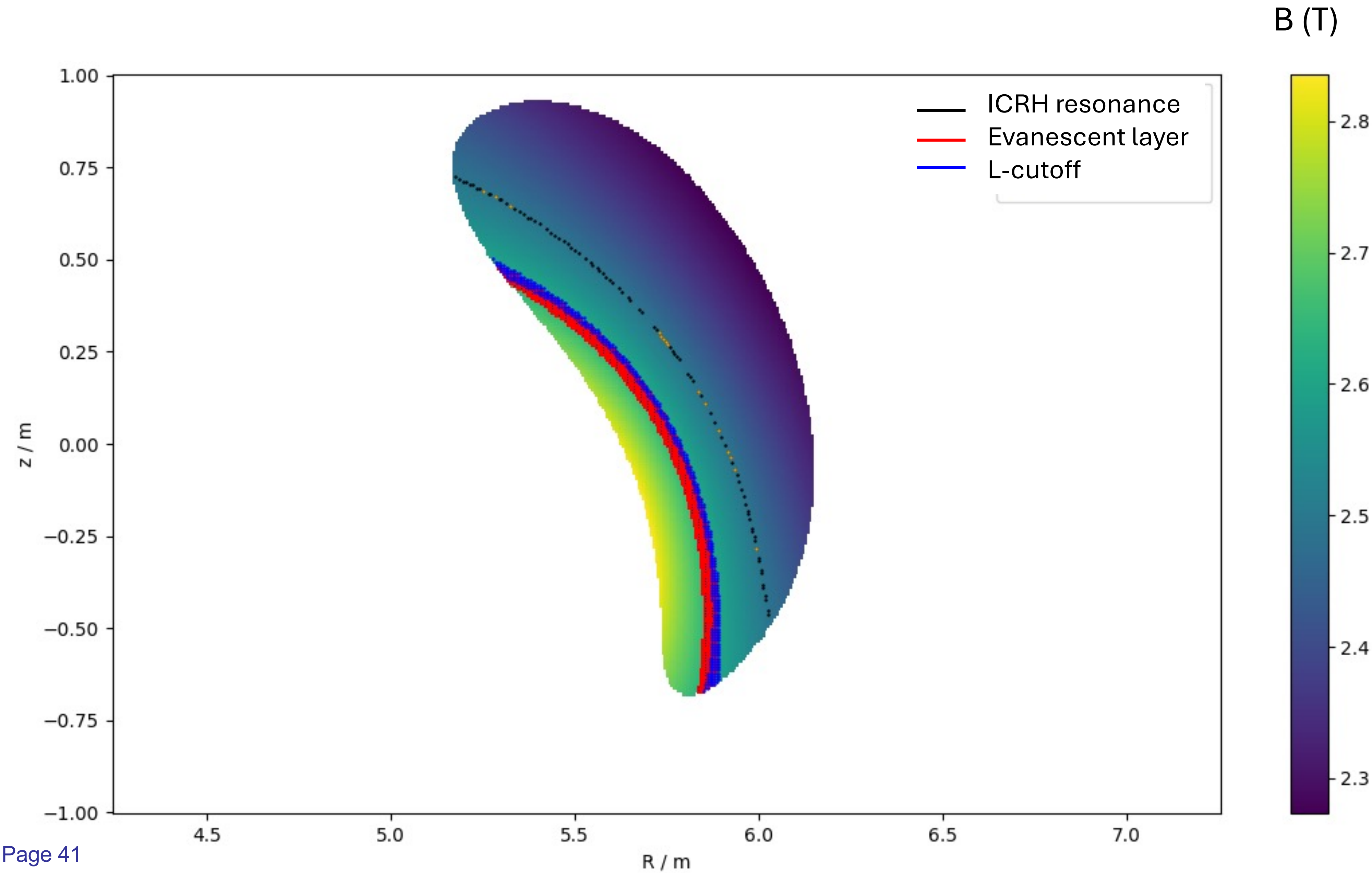
7% H



B (T)
2.8
2.7
2.6
2.5
2.4
2.3
ICRH resonance
Evanescent layer
L-cutoff
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
z / m
4.5
5.0
5.5
6.0
6.5
7.0
R / m

^{4}He-(H)

10% H


B (T)
ICRH resonance
Evanescent layer
L-cutoff
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
z / m
4.5
5.0
5.5
6.0
6.5
7.0
R / m
2.8
2.7
2.6
2.5
2.4
2.3

^{4}He-(H)

15% H

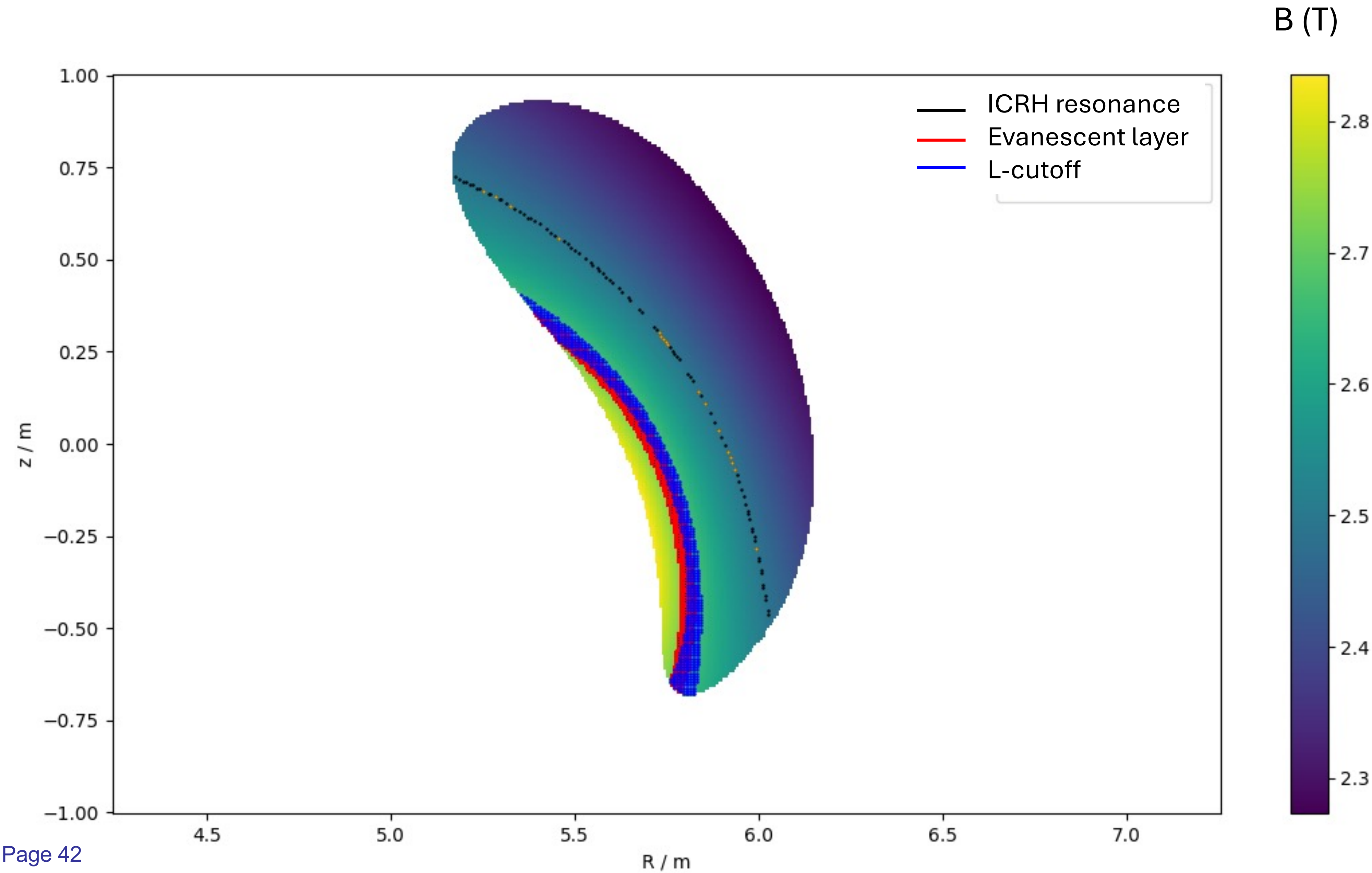
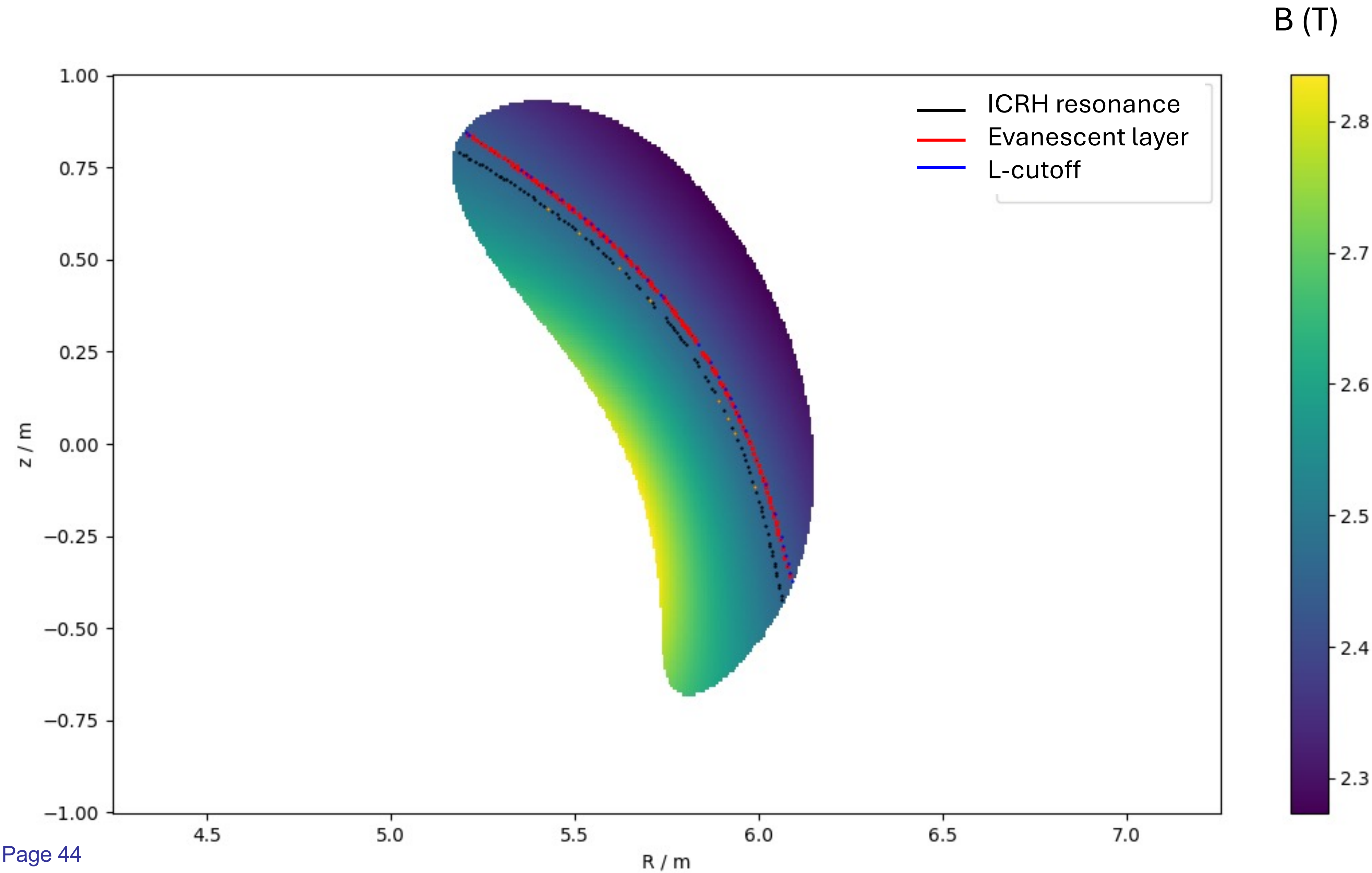

B (T)
ICRH resonance
Evanescent layer
L-cutoff
z / m
R / m
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
4.5
5.0
5.5
6.0
6.5
7.0
2.8
2.7
2.6
2.5
2.4
2.3

Illustration for the H-(^{3}He) scenario

H-(^{3}He)

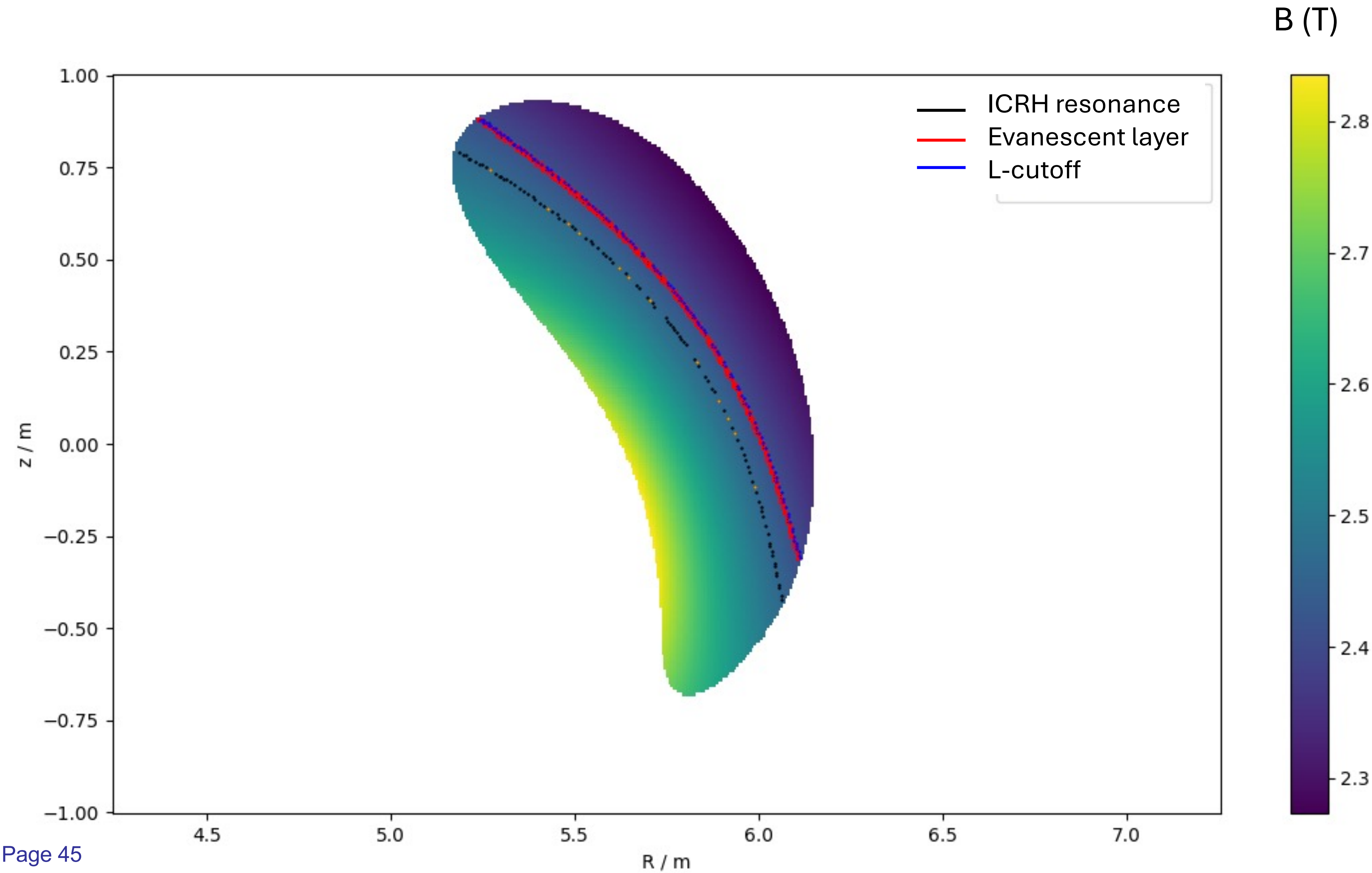
1% ^{3}He



B (T)
ICRH resonance
Evanescent layer
L-cutoff
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
z / m
4.5
5.0
5.5
6.0
6.5
7.0
R / m
2.8
2.7
2.6
2.5
2.4
2.3

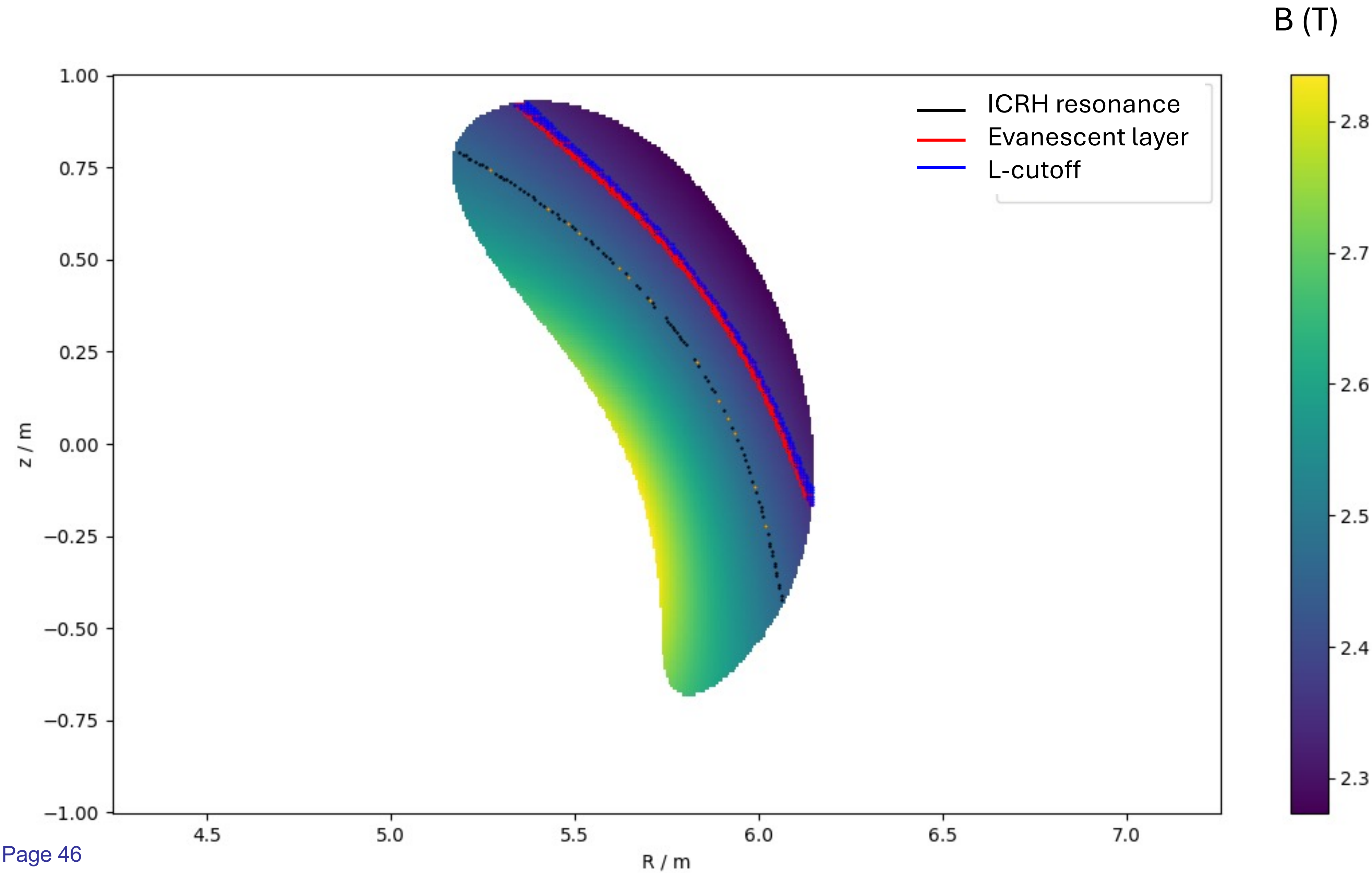
H-(^{3}He)

2% ^{3}He


B (T)
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
z / m
4.5
5.0
5.5
6.0
6.5
7.0
R / m
ICRH resonance
Evanescent layer
L-cutoff
2.8
2.7
2.6
2.5
2.4
2.3

H-(^{3}He)

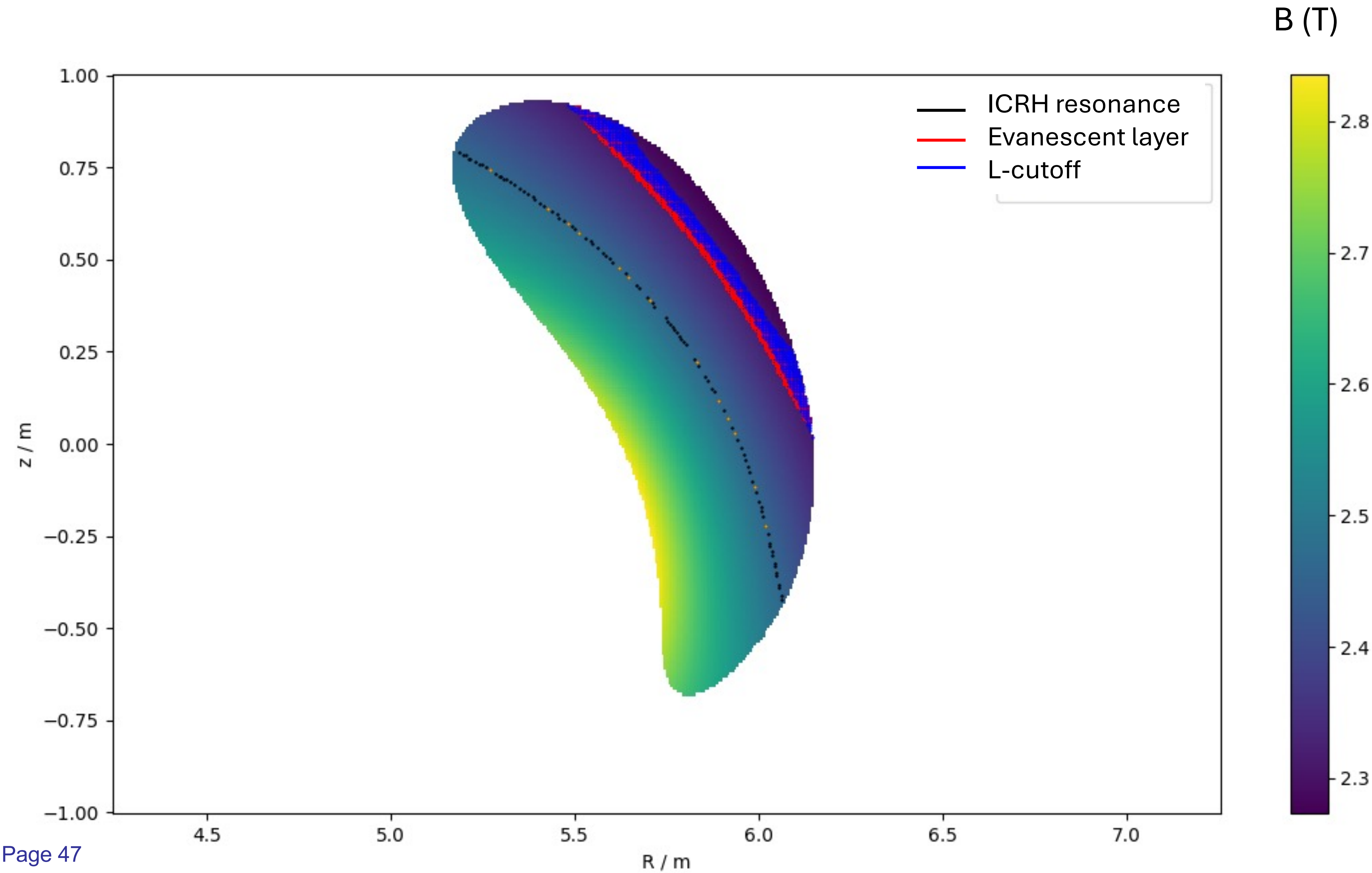
4% ^{3}He



B (T)
2.8
2.7
2.6
2.5
2.4
2.3
ICRH resonance
Evanescent layer
L-cutoff
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
z / m
4.5
5.0
5.5
6.0
6.5
7.0
R / m

H-(^{3}He)

6% ^{3}He



B (T)
ICRH resonance
Evanescent layer
L-cutoff
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
z / m
4.5
5.0
5.5
6.0
6.5
7.0
R / m
2.8
2.7
2.6
2.5
2.4
2.3

What does this mean in practice for W7-X ?

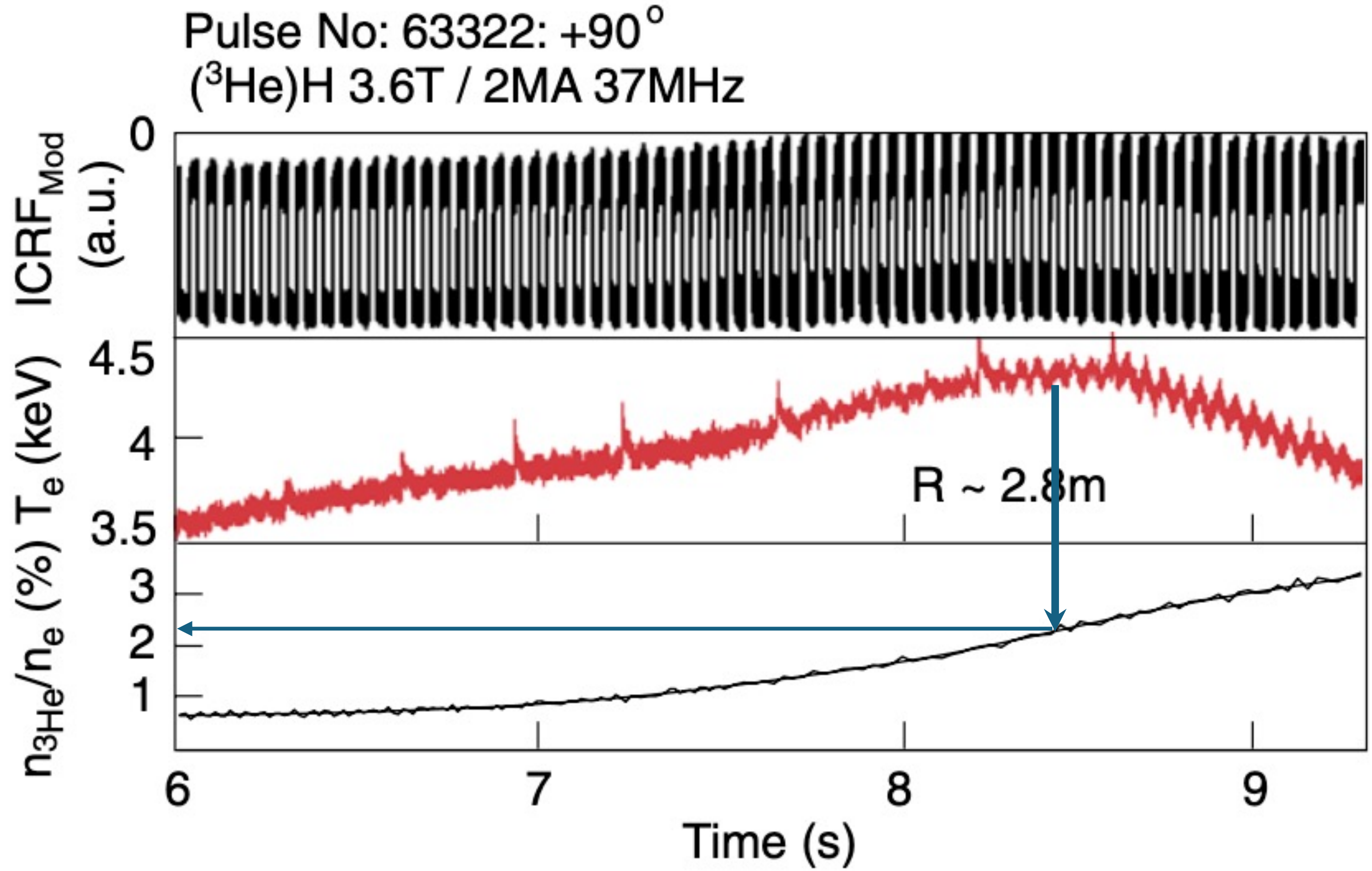
Estimated on the basis of the width of the resonance layer:

H minority in ^{4}He for up to ~ 5-6 % H in ^{4}He

^{3}He minority in H for ~ 2-3% ^{3}He in H

Estimates fit with results from JET for H-(^{3}He) heating

Optimal ICRH power deposition at ^{3}He concentration of ~ 2%



M.Mayoral, Nucl. Fusion 46 (2006) S550–S563

ICRH Operations in OP2.3

Ion Cyclotron Wall Conditioning

^{4}He-(H) heating experiments

Plasma Startup ICRH + NBI

H-(^{3}He) heating experiments

Consequences for operations

Given the reduced sensitivity on the minority concentration :

- ^{4}He-(H) heating should be demonstrated first.

Need a machine with plasmas containing nearly pure ^{4}He

- Wall loaded with ^{4}He :
  ICWC should also be tested -> more homogeneous, more efficient ?
- **Need precise and reliable H concentration measurements**

For testing H-(^{3}He) plasmas :

- **Need precise measurement of ^{3}He concentration in a ^{4}He plasma:**
  Chris Klepper and colleagues, ORNL, together with IPP colleagues

Consequences for operations

Ideal sequence of operations

1st set of experiments (1 session?) : ICWC

2nd set of experiments (2 sessions?) : ^{4}He-(H) at the end of a 4He week (or weeks)

- **First wall should be free of H**
- Using a well calibrated gas inlet (at antenna ?) and precise concentration measurement. Preceded by ICWC pulses.

3rd set of experiments (2 sessions ?) H-(^{3}He)

- **Only feasible if we have a precise ^{3}He concentration diagnostic**

4th set of experiments (1 session) ICRH startup followed by NBI takeover

3-ion heating experiments ^{4}He-(^{3}He)-H will need:

- **Precise H and ^{3}He/^{4}He measurements**

ICRH sessions should be under the exclusive control of the ICRH team

Interleaving with other experiments must be avoided to ensure that the plasma conditions remain stable and under control.